DESERTIFICATION AND ITS CONTROL

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FOREWORD

I am happy that the Indian Council of Agricultural Research is bringing out a publication on "Desertification and Its Control" on the occasion of the United Nations Conference on Desertification. I would like to congratulate the United Nations and its specialized agencies for focusing attention on this important problem.

About one-third of the world's land surface today is in the grip of deserts. The man-made deserts alone, total about 9.1 million sq km in area. In India, the arid zone occupies nearly 12 per cent of the total area sustaining a human population of over 19 millions and livestock of over 23 millions. According to a recent study on Desertification completed at the Central Arid Zone Research Institute, it has been found that 4.35 per cent of western Rajasthan has already been affected by the processes of desertification and that another 76 per cent area is moderately vulnerable to desertification.

An important factor in the accentuation of desert condition is the escalation of human and livestock population. The human population in the Rajasthan desert itself has increased from 3.42 millions in 1901 to 8.84 millions in 1971. In fact, the Indian desert is one of the most thickly populated among the desert areas of the world.

During the past few years, several studies on the problems of arid zone have been promoted by international organisations such as the UNESCO and FAO. In India, the Central Arid Zone Research Institute was established at Jodhpur in 1959 to conduct basic and applied researches on the problems of arid areas. As a result of the intensive work carried out at this Institute, considerable experience has been gained on different aspects of the problem. The scientific and technical basis for dryland agriculture and horticulture, grassland management, livestock farming, afforestation and water harvesting have been explored with a fair degree of success. Operational research projects have also been initiated in the arid areas of Rajasthan to expedite effective transfer of technology.

However, despite useful contributions and efforts by research organisations, we have not been able to achieve a significant breakthrough on the development front. A major reason for this is the lack of an integrated approach. The available scientific information on the rational use of eco-system resources are yet to be converted into action programmes. The development of the desert area, thus, is a major task which covers programmes under many disciplines and consequently several departments. In view of its magnitude and complexity, it is important to have comprehensive time-phased plans of development with a clear knowledge of relative priorities.

The ultimate success of all our programmes will depend on the extent of involvement of the desert people themselves who have been fighting for survival braving the sun, wind and lack of water over the centuries. Backed by science and technology they can bring about the required transformation.

I hope the papers contained in the book will be found useful by all interested in the problems of desertification and its control. The message of the papers is clear, namely, "Given the will and appropriate action, the desert can bloom". It is now up to everyone concerned to take action to convert the potential into reality.

New Delhi
26 July, 1977

SURJIT SINGH BARNALA
Union Minister for Agriculture and Irrigation

PREFACE

THE arid zone of India occupies an area of 3.2 lakh sq km of hot desert, mostly in Rajasthan, Gujarat, Haryana and Karnataka and 0.7 lakh sq km of cold desert in Ladakh. In Ladakh, extreme aridity combined with low temperature limits the possibility of growing crops to about 5 months in a year. Hence, the strategy for agricultural development in Ladakh has to depend largely on the cultivation of quick-growing cereals, oilseeds and fodder crops and the rearing of goats, giving Pashmina wool. The hot desert regions, in contrast, have an abundance of sunshine, land and soils capable of responding to management, well-adapted grasses and trees, excellent breeds of sheep, goat and cattle, and considerable reserves of ground-water. Water and not land, is the principal limiting factor and hence all attempts have to be focused on maximising income per litre of water This will be possible only if the ecological balance is not further disturbed and a proper land-use pattern is adopted.

Let me cite three examples to illustrate the trends which are aggravating the unfavourable consequences of aridity. First, the area used exclusively for grazing in Western Rajasthan has dropped from 13.09 million hectares to 11.04 million hectares during 1951-61, while the population of grazing animals increased during the same period from 9.4 millions to 14.4 millions. The same trend of diminishing grazing area and rapidly expanding grazing population is persisting. Secondly, while most of the land in the arid zone is fit only for forestry or range management, land is increasingly being brought under cropping. The areas cropped rose from 26 per cent in 1960 to 38 per cent in 1970, thus extending cultivation even to submarginal areas. Thirdly, the area under forests is only 2 per cent although the extent of land classified under barren uncultivable waste is 28 per cent and cultural waste is 18 per cent, all of which could be planted with tree species like *Acacia tortilis*, *Prosopis juliflora* and *Eucalyptus* sp. Fruit trees like *ber* (*Zizyphus mauritiana*) and pomegranate can also be grown.

Afforestation has to be the focal point for reclaiming the desert. Techniques for soil and water conservation and for sand-dune stabiliza ion are fortunately available today. Large scale planting of shelter-belts could help to minimise wind erosion and decrease the dust over the desert. Scope for the establishment of pastures and grazing lands is great and strip cropping involving the setting up of permanent grass strips to prevent wind damage will help to increase the yield of crops like *bajra* (*Pennisetum typhoides*) and *moong* (*Vigna radiata*) substantially. If steps of this kind can be taken, it may be possible for the nomadic tribes to start leading a more settled life.

Rajasthan has many fine breeds of sheep and research has shown that appropriate cross-breeding procedures can help to improve the yield and quality of wool and of mutton. Fortunately, techniques for artificial insemination have been developed and hence more widespread genetic improvement programmes are possible.

An important need in the desert areas is the preservation of organic matter for the soil. Unfortunately, due to deficiency of fuel, the available organic wastes are generally used for burning and trees are cut in an unplanned manner. It is here that more extensive research and extension efforts on the utilization of solar energy for purposes like heating, cooking, lighting and distilling water will be of great value. Often in the desert areas, the water is saline and people have to walk several miles every day to fetch sweet water. Solar stills to produce water for drinking in such area will be a great boon to the villagers.

Sophisticated techniques for raising crops in desert areas with very limited quantities of water are now becoming available. These involve cultivation of vegetables and high-value crops under air-inflated polyethylene houses using economic methods of water supply like drip or sprinkler irrigation. Since the Lathi aquifers of the Thar desert are rich, it may be possible to develop efficient water-use systems at least for raising community nurseries of different crops so that transplanting can be done if there is a delayed onset of monsoon and for purposes like the cultivation of vegetables and seed production.

Unfortunately, we have no arrangements now either to mitigate the rigours of a bad season or to derive maximum advantage from a good season. For example, 1977, because of the good monsoon, provides a unique opportunity for planting in the desert a large number of trees and for seeding large areas with grasses. In spite of the shallow nature of the soils and the calcium carbonate pans which occur in the subsoil, thereby increasing run-off and reducing infiltration, abundant moisture will be available to facilitate the establishment of trees, shrubs and grasses.

The present publication brought out on the occasion of the United Nations Conference on Desertification provides a synoptic account of the work done in India on problems relating to the Rajasthan desert. I am grateful to Dr H.S. Mann, Director, Central Arid Zone Research Institute, Jodhpur and his band of devoted scientists of CAZRI as well as to the other contributors to this volume for the trouble they have taken to prepare the material. Besides the editorial and production staff of ICAR whose names are listed in this volume, Dr K.S. Bedi served as Honorary Editor and paid detailed attention to the language aspect of the presentation. My sincere thanks are also due to him. I hope this volume will be found to be of some value by all interested in the problems of the desert and the challenge they pose to the scientists, and to those involved in the development and proper utilization of resources.

New Delhi
27 July, 1977

M. S. SWAMINATHAN
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INTRODUCTION

H. S. MANN

THE Indian desert, a hot-season rainfall region, situated in the north-west covers about 28,600 km². The western scarp of the Aravalli Range, running in a NE-SW direction, is the geomorphic as well as the climatic (500 m isohyte) boundary of the desert in the east, whereas in the west it merges into the Pakistan desert. In the north, the desert extends into the Punjab and Haryana States and in the south into the Gujarat State.

Archaeological evidences suggest that the onset of aridity was the major cause of the extinction of the Riparian and Harappa-Kalibangan civilization. A well-knit river system existed in the desert until recent times. The deterioration of climate, the rise of the Himalayas, the lowering of the Aravallis, *important changes in the river* systems, e.g. the diversion and disappearance of three classical rivers (the Yamuna, the Saraswati and the Ghaggar), and the lowering of the underground water-table caused increased aridity in the area (Wadia, 1960). Krishnan (1952) observed that arid conditions might have set in between 4000 B.C. and 1000 B.C. Palynological evidences indicate that the desertification process set in during the late Cretaceous (Lukose, 1972; Gurdip Singh, pers. comm.). Biotic interference of the natural resources further accentuated the xeric conditions at a later stage. There is clearly much scope for further work.

There are archaeological evidences to suggest that Rajasthan, Punjab and Gujarat were inhabited by man during the Palaeolithic period. Hand-axes made of quartzite have been found from Jaipur and Indargarh. These tools must be at least 2,00,000 years old (Sankalia, 1952). Misra and Rajaguru (1975) consider that the Middle Palaeolithic culture of the Luni Valley of the Rajasthan desert is of late Pleistocene age. There is considerable evidence that Rajasthan was inhabited by man early in Holocene times, though it is not certain whether there was cultural continuity from Palaeolithic to this Mesolithic period (c.f. Tilwara, 70°5′E, 25°52′N) estimated roughly to 5000 B.C. The Harappan culture has been traced at Kalibangan, situated on the bank of the 'lost' Saraswati river. Radio-carbon dating indicates that this culture flourished around 2700 B.C. (Satya Prakash, 1964); Harappan *culture is generally placed at 2300–1750* B.C. More than a hundred sites of this culture have been discovered in the Ghaggar bed in the northern desert. It is thus clear that the roots of man in the Rajasthan desert are fairly old.

The notion that the Rajasthan desert has been advancing at the rate of 1/2 a mile per year for the last 50 years, as claimed by the Planning Commission in its First Five-Year Plan Report, is fairly widespread, but lacks scientific unanimity, mostly because of terminological controversies. The increase and decrease in wind-blown surfaces have been illustrated by a comparison of old and recent survey maps which indicated an extension of the desert towards the east (Singh, 1952). However, the fact that in some areas sand formations have developed, whereas in others they have diminished or vanished, is no conclusive proof of the movement of the desert. Recently, a study based on socio-economic parameters has also yielded evidence that there may not be any scientific basis of the view that the Rajasthan desert has been spreading in the north-easterly direction (Mann, Malhotra and Kalla, 1974). Scientists are, however, unanimous with regard to the accentuation of xeric conditions within the desert owing to over exploitation of the vegetation and land resources. The dearth of sufficient climatic data do preclude the establishment of definite climatic shifts, although indications of some climatic fluctuations in the past have been noticed.

The major factors of desertification (accentuation of the desert conditions) within the desert are the escalation of human and livestock population and their activities, besides the climatic and geomorphological factors. The human population within the Rajasthan desert has increased from 3.42 millions in 1901 to 8.84 millions in 1971—a growth rate of 158 per cent, and this rate is much more (125 per cent) in comparison with the whole of the Rajasthan State. The density of population in various desert districts vary from 4 in Jaisalmer to 157 persons per km² in the Jhunjhunu district. The human population in the desert is largely rural; the ratio of urban to rural population came to 3.90, 4.50 and 4.33 respectively in 1951, 1961 and 1971. About 79 per cent of the population is engaged in agriculture. One of the crucial bottlenecks is that we are unable to find occupations for the ever-increasing human population. The occupations do not require the use of water, land or domestic animals, e.g. large-scale mining, oil and natural gas, tourism, etc. which could earn a livelihood for the people without becoming a denuding stress on the land. Agriculture and animal husbandry remain the major sources of income of the people in the Rajasthan desert. Owing to the increasing population and related economic factors, marginal lands have been brought under the plough and this trend is continuing.

The increasing human population is a serious stress, particularly on the vegetal resources of the desert. The trees and shrubs and even their roots are indiscriminately cut by the rural population for fuel, top feed, thorn fencing and the construction of thatched hutments. It has been estimated that the requirement of the people in the desert in respect of the woody biomass has increased from 1.85 million tonnes in 1951 to 3.33 million tonnes in 1971. The desert people have developed peculiar food habits. All the available air-dried seeds and pods of the trees are used as delicacies. The seeds of *Acacia senegal* (*kumat*), the fruits of *Capparis decidua* (*karir*) and the pods of *Prosopis cineraria* are harvested. Almost all the fruits of *Zizyphus nummularia* (*ber*, *jhadberi*) growing in accessible parts of the desert are harvested for human consumption. The seeds of grasses, e.g. *Panicum turgidum*, *P. antidotale*, *Cenchrus biflorus* and *Echinochloa colonum*, are mixed with millet for making *chapatis* (unleavened cakes) especially during drought years. The grass seeds are supposed to add to the nutritive value of the food. The intensity with which seed collection is made for direct human consumption throughout the desert region seriously affects the natural process of regeneration of the desirable plant species in the inhospitable terrain. Along with efforts to evolve technology for increasing vegetable production locally, the problem has to be tackled also by formulating a suitable educational programme for the masses.

Livestock population far exceeds human population in arid western Rajasthan. It increased from 9.4 millions in 1951 to 15.5 millions in 1972. The goat and sheep populations ranged from 57.1 to 69.3% during this period. Owing to continued droughts during 1967–71, with the consequent migration and mortality, the number of cattle fell heavily (10.8% decrease), but the number of hardy animals, e.g. the goat, increased substantially (34% increase). The data thus not only reveal a preponderance of the goat and sheep populations in the arid Rajasthan but also point to their increase during the years of drought. The goats are the desert-makers *par excellence*, eating every bit of green or dry vegetation.

Because of cultivation of marginal lands, overgrazing, and the depredations of field rodents, the compact, stabilized sand over the inter-dunal and dune lands is loosened to be carried away by the strong desert winds. It has been estimated that dust blowing from the surface to a height of 3 metres on a dust storm day varies from 0.58 to 4.20 quintals per hectare at Jodhpur and 5.11 quintals at Jaisalmer during the normal years. In exceptionally dry years, as in 1970, the germinated *kharif* crop was buried under shifting sands over vast areas in Jaisalmer, Bikaner and Barmer districts. As recommended by the National Commission on Agriculture, it is important to work out a policy whether arid lands receiving rainfall lower than 300 mm per annum or so should be cultivated or used as rangelands for livestock.

Another important consequence of overgrazing is the interference in natural regeneration and succession of vegetation, especially the grass species. The lush monsoon vegetation in the desert may seem an inexhaustible source of foraging material for the very large number of domestic livestock. Most of the species, e.g. *Tephrosia purpurea*, *Indigofera cordifolia*, *Tribulus terrestris*, *Crotalaria burhia*, *Cyperus* spp., are not only inedible or unpalatable to livestock, but compete severely with the perennial species of nutritive grasses and, consequently, the landscape is infested by low-ranking unpalatable annuals, thus decreasing vegetation production and affording poor coverage for soil conservation.

Pests join man and his livestock in depleting the vegetative resources of a region. Rodents are an important factor in desertification. Besides maintaining a perpetual pressure on the natural vegetation for their food, because of their burrowing habits, rodents significantly induce soil erosion (Prakash, 1976). Their fossorial propensity is injurious to soil conservation. Out of 17 species of rodents found, 10 are of economic importance. In various desert habitats, their number fluctuates from 7.4 to 523 per hectare and their biomass from 435 to 2,641 g/ha. Their dietary demands (1,044 kg/ha) are so insatiable that a resident population of *Meriones hurrianae* during the monsoon can consume the total forage production of an area (1,100 kg/ha), thus virtually leaving nothing for the livestock. Rodents also ravage the germinating and growing vegetation, feed on seeds, thus lowering the regeneration potential of the vegetation and even debark 20–30 per cent of 1–8-year-old saplings planted for reforestation of the dunes. The merion gerbils alone are estimated to excavate 61,500 kg of soil per day per km^2 in cultivated fields during summer and 10,43,800 kg/day/km^2 in uncultivated areas.

The locust menace, though under control during the last decade, is known to cause havoc in the desert and its adjoining areas. In the past, locust swarms entered the Rajasthan desert in the hot months of May and June and devoured whatever green vegetation that might still be fighting for survival, leaving the sandy desert to the mercy of the strong summer winds. As it is well-known, even large trees are totally defoliated by locusts and they sometimes collapse owing to the sheer weight of the tiny marauders. Thus, historically, the desert locust has been one of the major agents of accentuation of xeric conditions.

The scientific exploitation of ground-water in the Indian desert is another important matter. The occurrence and the quality of the ground-water at a particular site are mainly dependent on the mode of formation and nature of the aquifer and its relation to the overlying beds. The water-bearing rock formations of the Rajasthan desert are the Aravalli slates, schists, quartzite, phyllite, Malani rhyolite and granite, Jodhpur and Lathi sandstones, and Bilara limestone. In a major part of the desert, ground-water generally occurs in small, isolated pockets and not as a continuous body. Only a few areas have been recognized for moderate to large-scale ground-water development, e.g. the Jawai-Sukri river alluvium of Jalore, the alluvial sediments of Doli-Jhanwar-Pal area, the Lathi sandstone of Jaisalmer, the Borunda limestone and the Jodhpur sandstone in the Jodhpur-Phalodi region.

Utilization of ground-water

It has been estimated that 47.78 per cent of the total exploitable ground-water potential is tapped in various desert districts (Das Gupta *et al.*, 1973). Jalore, Jodhpur, Pali and Sikar are the only districts where more than 50 per cent of the total exploitable water potential is utilized. About 7 per cent of the total exploitable water is utilized for irrigation and 13 per cent for human and livestock consumption. Considering the needs for irrigation and human and livestock consumption, it appears that in a few years the exploitation of ground-water will exceed the annual recharge. There is, therefore, an immediate need to evolve a sound ground-water exploitation policy.

The water-scarcity problem is compounded by its quality aspects. Saline ground-waters up to and over a salinity level of 10,000 micromhos (about 6–7 grammes of soluble salts/litre) are being used in the desert for growing barley and 'Kharchia' wheat and it is estimated that the area covered by saline-water irrigation is nearly 0.4 million ha. The continued use of these waters renders the soil saline or saline/sodic. Loamy soils tend to accumulate a higher concentration of salts and also show a high SAR. The soils which accumulate salts up to 10–16 millimhos ECe, however, attain a salinity level of 2–6 millimhos ECe after one or two rainy seasons, depending on the soil texture, and become fit again for cultivation. However, the salts leach to deeper depths and continue to accumulate there and after several decades of cultivation, areas with loamy and heavier-textured soils invariably become unfit for cultivation.

In a recent study on desertification, completed at the Central Arid Zone Research Institute on behalf of the UNESCO, it has been found that about 9,290 km^2 or 4.35 per cent of the western Rajasthan has already been affected by the processes of desertification. 1,62,900 km^2 or 76.15 per cent of the area has been categorized as highly and moderately vulnerable and 41,692 km^2 or 19.5 per cent of the area is moderately to slightly vulnerable to the various processes of desertification. The shifting of sand and soil erosion by winds are the major causative factors. In the study area, the Luni Development Block, it was observed that during the last 18 years, sand movement leading to a further accentuation of undulations has taken place over 166 km^2. The recent sand-shifting has led to an increase in the thickness of the soil on the previously created fence-line hummocks by 15 to 30 m and have enhanced their width by 1–2 m. The process of desertification is rather revealing in the vegetal component of the ecosystem. The productive climax plant associations have changed to degraded vegetation types with the increase of unpalatable species. Certain areas of the desert, belonging to the slight-vulnerability category, are also associated with water erosion.

The knowledge of various disciplines have been gained and the technologies for the development of the arid regions have been evolved by research institutions and they are reflected in the formulation of policies for development. A recent report of the National Commission on Agriculture on Desert Development, and the initiation of the Drought-Prone Area Programme in collaboration with the World Bank are important landmarks in this field.

This publication has been prepared for the UN Conference on Desertification to be held at Nairobi in August-September 1977. The contributions reflect the scientific work done and the available technologies. While scientific research is being intensified for discovering methods of harnessing the resources of the arid and semi-arid areas, operational research projects that have been initiated by the Indian Council of Agricultural Research in the region are likely to pave the way for the down-to-earth application of the available knowledge for the good of the desert people.

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2

ORIGIN AND HISTORY OF THE RAJASTHAN DESERT–PALAEOBOTANICAL EVIDENCE

VISHNU-MITTRE

THE origin and history of the Rajasthan desert cannot be divorced from the origin and history of aridity in the vast geographical expanse not only in the western part of the Indo-Pakistan subcontinent but also in a large part of the central and the peninsular region almost down to the tip of Cape Comorin where the tropical dry deciduous and thorn forests occur. In this vast area, the summer temperatures are high and the precipitation is low, but the western part of the subcontinent has, in addition, lower winter temperatures accompanied with precipitation in winter, autumn and spring. In the latter part, the influence of Mediterranean climate (a mild winter rains during the cool seasons of the year and a hot dry summer), which tends to inhibit or slow down the growth of the woody species and prevents the growth of the non-woody plants, has been recognized. But for the typical Mediterranean climate in some parts of Baluchistan (Nok Kundi) in the extreme west of the subcontinent, moderate and attenuated Mediterraneity occurs in the rest of the western region of the subcontinent (Meher-Homji, 1973). Along side this, the influence of the temperate climate owing to the proximity of the region to the Himalayas in the north imparts a distinctive feature to the climate of the western region from the climate in the arid, semi-arid region in the south of the subcontinent.

The present vegetation in the western part of the subcontinent has a substantial proportion of the Saharo-Sudanian-Mediterranean element (40–42%) in western Rajasthan and Kutch, a gradual decreases of which is noticeable in the floristics of the Aravallis (25%), Madhya Pradesh (4%), northern Gujarat (19%), the Deccan (13%) and the Coromandel coast (2.5%). The Mediterranean element is non-existent in the peninsular region, though the tropical African element does occur. On the other hand, the Indo-Malayan element with concentration in the ever green, semi-evergreen forests of north-east India and of the west coast exhibits a proportional decrease in the arid, semi-arid regions with pronounced reduction in the western part of the subcontinent (Meher-Homji, 1973).

The present position of floristics and climate in western India has either remained static over the geological history or is reminiscent of the once-exclusive occurrence of the Indo-Malayan floristics with its characteristic climate in the entire subcontinent. It began to recede as a result of change in climate sometime in the geological history resulting in the invasion of the Saharo-Sudanian-Mediterranean element. The reconstruction of the past plant life from palaeobotanical discoveries indeed reveals that both the present-day floristics and climatic pattern have not been static during the geological past (Vishnu-Mittre, 1969).

RAJASTHAN DESERT DURING THE GEOLOGICAL AGES

The discovery of fossils of *Mesua*, *Garcinia* and *Calophyllum* (Lakhanpal and

Bose, 1951) from the Fuller's earth in the Barmer District and *Cocos* from Kapurdi in the Jodhpur District (Kaul, 1951) in western Rajasthan and dated back to 60 million years (Eocene Age) is of significant interest. The first three are important members of evergreen, semi-evergreen forests in the Western Ghats and north-east Assam under an annual rainfall regime of about or above 2,000 mm, with a very short dry period or without it. A species of *Calophyllum* also occurs in lagoons. *Cocos* is highly reminiscent of the marine environment not very far from Jodhpur. An equable, warm to moist tropical climate is suggested by the plant fossils to have occurred in the present Rajasthan desert about 60 million years ago (Vishnu-Mittre, 1969).

In spite of the absence of any palaeobotanical evidence thereafter, particularly during the mid- and late-Tertiary and a large part of the Quaternary of Rajasthan, the mid-Miocene to Pliocene evidence from north-western India of the floristics of semi-evergreen elements, such as *Dipterocarpus*, *Cyanometra*, *Milletia*, *Fissistigma wallichi* and of *Anisoptera* which occur today in Assam, Bengal, the Andamans Islands and along the west coast and the Pliocene evidence of *Dipterocarpus*, *Podocarpus*, palms, *Lycopodium*, *Selaginella* in Kutch (Ghosh and Ghosh, 1958; Mathur and Mathur, 1969; Lakhanpal *et al.*, 1975) are highly suggestive of the continuation of the semi-evergreen forests in north-west and western India until the beginning of the Quaternary, about 2–3 million years ago (Vishnu-Mittre, 1969, 1976). The region now occupied by Rajasthan, too, had a similar vegetation and climate as in the north-west and Kutch. During this period, the immigration of the temperate flora had also commenced in the emerging Himalayan mountains.

The period from the end of Pliocene to the end of the last glaciation, the shortest period in geological history and characterized by repeated fluctuations in climate, is indeed most important for the floristic history, but unfortunately without any palaeobotanical evidence from western India. The palaeobotanical evidence beginning from the end of the last glaciation about 10,000 years ago reveals that the desert with arid and semi-arid plant communities had already established itself as known through pollen analysis of the salt lakes, Lunkaransar, Didwana and Sambhar, in northern Rajasthan and of subsequent date from the Pushkar Lake in central Rajasthan (Singh *et al.*, 1974; Vishnu-Mittre, 1974a,b,c; Vishnu-Mittre, 1976).

The analysis of the palynological data in the light of vegetational survey of Rajasthan by Gaussen *et al.* (1972) reveals that the vegetational development in the vicinity of Lunkaransar largely comprised members of the *Calligonum* series on active and stabilized sand-dunes and of *Prosopis-Capparis-Zizyphus* series on the sandy alluvium in the vicinities of Didwana and Sambhar lakes. Today, both occur under annual precipitation of 150–400 mm, with the dry period extending over 9–11 months a year, with mean temperature of the coldest month between 15 and 20°C or less than 15°C. The rocky ground with shallow soil had *Maytenus* growing over it and the saline/alkaline areas were overgrown with *Tamarix*, the members of the Chenopodiaceae and some grasses and sedges. The overall aspect was of a desert Savannah.

The intensity in the sand-dune formation as a result of the renewed violent aolian activity about 5,000 years ago caused the invasion of *Calligonum* series in the Didwana area, but this series did not invade the area of the Sambhar Lake. A comparative study of the three pollen diagrams suggests that the moisture gradient, more or less as at present, had already been established in western Rajasthan.

The central Rajasthan area in the vicinity of Ajmer was a meeting-ground for the *Calligonum* series, the *Prosopis-Capparis* series, and the *Anogeissus* series. The last-mentioned has in recent times replaced the *Calligonum* series, thus suggesting a slight change in precipitation (from 400 mm to the present level), and with a slight reduction in the dry period but the temperature of the coldest month remaining the same.

The palaeobotanical work in the adjoining Gujarat State, particularly from the Nal Lake near Ahmedabad (Vishnu-Mittre and Sharma, 1975) and from Malvan (Vishnu-Mittre and Sharma, 1975) has brought out a grassland Savannah of semi-arid type since the end of the last glaciation.

From the above account it appears that the desert had already established itself before the biotic factor had become effectively operative. The Palaeolithic man did exist here and the Mesolithic man had settled on the sand-dunes or the sandy alluvium about 6,000 years ago (Misra, 1971). The urbanization in the desert commenced first with the Harappans who did find the climate harsh enough to allow them to cultivate barley most suited to a climate not hospitable to other crops (Vishnu-Mittre, 1974a, b,c; Savithri, 1976). They had also utilized gypsum to fertilize the sandy soils (Savithri, *op. cit.*). Finding that the vegetation around comprised scrub jungles most suitable only for inferior-quality fuel, they had to import timber trees of teak, *Boswellia serrata*, *Dalbergia*, etc. from the Aravallis or from eastern Rajasthan (Savithri, *op. cit.*). It is from their time onwards that the destructive impact of biotic factor began to be experienced by the plant life around. The end of their civilization was largely brought about by natural phenomena resulting in changes in the river courses, the cutting off their water-supply and rendering dry the old rivers which, in course of time, were covered by the advancing sands (Vishnu-Mittre, 1974c). Where the minimal water-supply was still available, cultures subsequent to the Harappans did continue, e.g. the Rangmahal culture, struggling hard and putting up with the waning water-supply until they gave in.

ORIGIN OF THE DESERT

There is no positive palaeobotanical evidence presently available for the time and circumstances which led to the origin of the desert. The history outlined above amply suggests that it must have originated sometime between the end of the Pliocene and before the end of the last glaciation. It is during this period that northern India had experienced repeated fluctuations, both in temperature and precipitation, the impact of which upon western Rajasthan cannot be overlooked. In the absence of palaeobotanical evidence this point cannot be stretched any further. However increasing trend in aridity witnessed since the Eocene times which had caused an increase in the deciduous element in the evergreen, semi-evergreen forests and the sudden emergence of desert conditions in the Rajasthan desert at the end of the last glaciation strongly suggests that the climatic stage of aridity in this region had set in sometime during early to mid-Quaternary. And it is during this period that western Rajasthan had turned into a desert.

CONCLUSION

The palaeobotanical evidence indicates an increasing trend in aridity since the Miocene times in western India. This trend was responsible for the increase in deciduous elements in the semi-evergreen forests with moist equable climate which had existed in the north-western and western India since Eocene times. It is during the early to mid-Quaternary most probably that the repeated fluctuations in temperature and precipitation caused the formation of the desert and overall aridity in western India. It is during this period that the Saharo-Sudanian and African floristic elements began to invade this region at the expense of decline and eventual extinction of the dense evergreen and semi-evergreen forests in western India and Rajasthan.

The creation of the desert was indeed the result of natural phenomena, and the early man had settled here under the desertic environment, with the precipitation gradient much as at present. The migration of the sand-dune formation activity from the west to the east of the desert has continued and the palaeobotanical evidence has been found of such an activity as recent as 5,000 years ago.

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3

EVOLUTION OF THE PATTERN OF HUMAN SETTLEMENT IN THE ARID AND SEMI-ARID REGIONS

V. N. MISRA

As a result of relatively recent research done in Rajasthan, Gujarat and Haryana, we now have a fairly good picture of the evolution of human cultures and of the pattern of human colonization in the arid and semi-arid regions of western India during pre-historic times.

There is no true Neolithic period in western India, because by the time the food-producing way of life was introduced into this region, man had already learnt the use of copper and bronze. So the Mesolithic period in this entire region is succeeded directly by Chalcolithic Age and in some cases by the Bronze Age.

Lower Palaeolithic period

The Lower Palaeolithic occupation in the arid and semi-arid zone is known from Gujarat and eastern Rajasthan. In Gujarat, Foote (1916) had discovered Palaeolithic implements at Pedhamli in the alluvium of the Sabarmati river in the last decade of the nineteenth century. In the Sabarmati, the Lower Palaeolithic implements have been found at several sites in its upper reaches near the Aravallis.

The available evidence shows that human occupation in Gujarat during the Lower Palaeolithic period was confined only to a few areas, and the population was meagre.

North of Gujarat, western Rajasthan is poor in the Lower Palaeolithic cultural remains. The only true Lower Palaeolithic site known is Govindgarh on the Sabarmati in the Ajmer district (Misra, 1965). Here, a small number of pebble tools, hand-axes and flakes were found in a gravel deposit. The region to the west of the Aravallis seems to have been colonized by man only towards the end of the Lower Palaeolithic. On the eastern side of the Aravallis, the cultural remains of this period are plentiful. In Mewar, rich Lower Palaeolithic assemblages have been found at Chittor and Nagari on the Gambhiri and the Berach, respectively, and at Kota on the Chambal. Numerous other sites are known on the Chambal, the Banas and their tributaries. In fact, Mewar is one of the richest areas in the country for Lower Palaeolithic cultural remains.

The Acheulian industry is found in the pebbly gravel and where the gravel has been eroded in the river-bed. At Chittor and Nagari, Acheulian implements can be collected from the river-bed in almost unlimited numbers. The concentration of Acheulian tools has been found up to Tonk on the Banas. Perhaps, the country near the foothills of the Aravallis was too densely forested to attract the Acheulian hunters.

The Acheulian assemblages are invariably made on quartzite and include hand-axes, cleavers, discoids, choppers, chopping-tools, Levallois and plain flakes, blades and cores. The Acheulian industry of this area represents a fairly developed stage.

It is difficult to know the precise climate conditions during this period. But cultural evidence would imply that rainfall was adequate and vegetation and game were plentiful to support the large Acheulian populations. The transport of large pebbles and boulders over long distances in the river-beds would also imply ample rainfall.

Middle Palaeolithic period

There is no reliable evidence of Middle Palaeolithic period in Gujarat outside Saurashtra. A few Middle Palaeolithic tools have been found in the central part of Kutch.

In eastern Rajasthan too, the evidence of Middle Palaeolithic culture is as yet meagre. Such tools have been found mostly at Rajiakheri and other sites on the Wagan river, and in very small number at Nimbahera on the Gambhiri river and at Chittor on the Berach river, all in the Chittorgarh district, and at Kota on the Chambal river in the Kota district. The implements are found in the sandy gravel which overlies the second white clayey deposit. They are made on quartzite and chert. The tools are made mainly of flakes and are much smaller and thinner than the Lower Palaeolithic tools and are also less rolled, suggesting that they were manufactured and used near the places of their present discovery. The paucity of Middle Palaeolithic remains in the Mewar region will indicate unfavourable environmental conditions during this period in this region.

In western Rajasthan, the cultural remains of Middle Palaeolithic period are plentiful. Tools of this period have been found at a number of sites in the Luni and its tributaries in the Pali and Jodhpur districts (Misra, 1968).

At Luni itself and at several other sites, Middle Palaeolithic tools have been found *in situ* in the cemented gravel. But they are more commonly found in the eroded gravel in river-beds. At Sojat, there are rich factory sites in the limestone hills where a plentiful supply of cherty material was available.

The raw material used for tools in this region is quite varied. It includes chert, silicified wood, rhyolite, felspar, porphyry and quartzite. The presence of evolved han-daxes and cleavers in small numbers suggests that human occupation in this area commenced towards the close of the Lower Palaeolithic period.

Upper Palaeolithic period

The evidence for the Upper Palaeolithic period is as yet very meagre in the whole of the arid and semi-arid belt, although some Upper Palaeolithic quartz implements have been reported from the Panchmahals district of Gujarat and at Budha Pushkar near Ajmer (Allchin and Goudie, 1971, 1974). It is believed that these tools were originally incorporated into the body of the dune and have subsequently slid down to the weathered surface.

The reason for the paucity of the Upper Palaeolithic cultural material in the arid and semi-arid zone probably lies in the extremely arid climate that prevailed during the terminal upper Pleistocene in this zone. Recent scientific studies of the dune fields in Rajasthan and Gujarat by scientists of the Central Arid Zone Research Institute, Jodhpur, the Geological Survey of India and the universities (Allchin and Goudie, 1971, 1974) amply show that at one time the arid climate prevailed over the whole of north-western India and that dunes were formed extensively from Pavagarh near Baroda in the south to Hissar in Haryana in the north.

Mesolithic period

This last phase of the Stone Age is best known in the arid and semi-arid zone. Far more sites of this period are known than of the earlier Stone Age cultures, certainly because of the considerable expansion of human populations. These sites, being of a comparatively recent age, are also much better preserved. Several human settlements of this period have been excavated, and have given us information of the living patterns during this period.

Evidence for Mesolithic period is known from Gujarat and Rajasthan. No Stone Age remains of any period are known from Haryana primarily because in the alluvial plains the basic raw material—stone—for the manufacture of stone tools was absent. And if any evidence existed in the past, it must be buried under the alluvium.

In Gujarat, nearly a hundred microlithic sites are known and they are distributed all over the alluvial plain. In northern and central Gujarat, microlithic sites are invariably located on the top of sand-dunes with enclosed basins. These dunes, where they have not come under cultivation, are covered by thorny scrub jungle and are well-stabilized.

Although microliths on dunes were first described by Foote as early as 1893, it was Sankalia and his co-workers who made the most significant discoveries in this field. The maximum information about the Mesolithic culture has come from the Sankalia group's work at Langhnaj (Sankalia, 1965).

The cultural materials at Langhnaj and at other sites occur all through in the dune sand, and the habitation deposit varies from 1.75 to 2 m. Though the culture revealed by the excavation is essentially homogeneous, three phases can be discerned within it.

A considerable amount of animal remains has been found at Langhnaj. Bovines bones are the commonest. The bones may belong to cattle (*Bos indicus*) or to Indian buffalo (*Bubalus bubalis*) or to both. Many of the bones were charred, and it is probable that most of the animals were killed for food.

Fourteen human skeletons found at the site all come from intentional burials. Except one which was laid in an extended position, all the skeletons were placed in a tightly flexed posture with feet brought well below the pelvic bones. None of the skeletons is complete, and some are very fragmentary, the bones often being disarticulated. The burial was, therefore, partial and secondary. Ehrhardt and Kennedy (1965) believed that breaks noticed on some skulls represent blows suffered by persons in life with sharp as well as with blunt weapons, and, therefore, the persons had been slain in battle. While Ehrhardt thought that some blows were struck post mortem and, therefore, suggested the practice of cannibalism, Kennedy thought that the cracks and fractures noticed on these crania and other bones could have been easily produced by the pressure of the debris over the bones and by natural agencies affecting bones. According to Ehrhardt, the skeletons share Mediterranid and Veddid racial features in a mixed form, and this racial mixing must have taken place at a very early stage. Kennedy agreed with this assessment, but he thinks that the Langhnaj people shared some of their genetic features with the Chalcolithic populations of the Indus Valley and the Deccan and with the Iron Age people of southern India.

Only one radio-carbon date,[1] TF-744, 2040 ± 110 B.C. is available from Langhnaj. This determination is obtained from mixed samples of uncharred bones derived from phases I and II, and as only the inorganic fraction was dated, the possibility of contamination is considered very high. However, since there is no evidence of domestication and, in the earlier levels, of any contact with the Harappa culture that flourished in the neighbouring Saurashtra and Kutch, the phase I of the site can be safely dated to a period before 2000 B.C. The presence of a copper knife in phase II suggests contact with the Harappa culture, and this phase may, therefore, belong to the first half of the second millennium B.C. Phase III, if the iron arrowhead and wheel-made pottery are not intrusive, will have to be dated to the latter half of the first millennium B.C., but it could also be much later.

To the north of Langhnaj, microlithic sites extend into the hilly country of the Aravallis. At Dhek Vadlo in the Sabarkantha district, for which alone data are available, most of the microliths occurred in the top 60-cm deposit, and no other materials were found. Geometric types were absent in the industry. The evi-

[1]Single radiocarbon dates mentioned in the text are based on the half-life of $5{,}568 \pm 30$ years. In the case of double dates from the same sample, the first date is based on the half-life of $5{,}568 \pm 30$ years, whereas the second date, given in parentheses is based on the half-life of $5{,}730 \pm 40$ years.

dence from these outlying sites supports the inference drawn from Langhnaj, namely that in the earlier phase of the Gujarat Mesolithic culture, pottery was unknown. In the south-east, microlithic sites extend into the hilly country of the Panchmahals district.

In Rajasthan, Mesolithic cultures are known from two regions. In Marwar, microliths have been collected from many sites, mainly in the Luni basin, but the most important site is Tilwara (72°50′ E : 25°52′N) in the Barmer district on the edge of the Great Indian Desert (Misra, 1971a, 1971b). This site lies on a low sand-dune in the old flood plain of the Luni river. The habitation deposit here is only about 50 cm deep. Here, two phases of occupation can be made out. Phase I between 15-cm and 50-cm depths from the surface, is characterized by an abundance of microliths and stray potsherds, whereas in phase II, between the surface and 15-cm depth, the microlithic industry declines and the wheel-made pottery is plentiful. Stray glass and stone beads also occur in this phase. It is possible that the pottery and glass beads actually belong to a later and post-Mesolithic phase and have got mixed up with the microliths because of the prolonged and constant movement of cattle and men on the dune. The stone industry is made of quartzite, chert and rhyolite, and is geometric in character. The size of many chert and rhyolite blades exceeds 5 cm and is in sharp contrast to the very small size of the blades and bladelets at most microlithic sites. The blades and bladelets were produced by the pressure flaking technique and show a very high standard of craftsmanship. Circular stone alignments with 2.25 to 3 m diameter suggest outlines of huts or windbreaks. The presence of hearths with charred animal bones in them further testifies to the habitational character of the site. Animal bones from the site, found in a limited quantity and in a poorly preserved condition, belong to the following species: humped cattle (*Bos indicus* Linn.), goat (*Capra hircus aegagrus* Linn.), pig (*Sus scrofa cristatus* Wagner), spotted deer (*Axis axis* Erxleben), hog-deer (*Axis porcinus* Zimmermann), jackal or dog (*Canis aureus* Linn. or *Canis familiaris* Linn.), and mongoose (*Herpestes auropunctatus* Hodgson). Among these, bones of cattle are the commonest. The fauna is a mixture of wild and domesticated species. The economy was therefore probably based on a combination of hunting and stock-raising. It, however, is not clear whether this position existed from the beginning or developed at a later stage. Carefully made spherical stone-balls are likely to have been used as missiles in hunting. No radio-carbon date is available from the site, and in the absence of any other datable material, it is not possible to estimate the antiquity of the site.

A few kilometres north of Tilwara, microliths of the same tradition have been collected from the shores of the Pachpadra salt basin by Gurdip Singh (personal communication). In view of the fact that saline lakes of western Rajasthan were initially freshwater lakes, there is a strong possibility of Mesolithic habitation sites being discovered on the shores of the Pachpadra and other salt basins. Eastward, microliths occur on the surface at Kanawas and Jadan midway between Pali and Sojat towns and in the limestone hills at Sojat (Misra, 1973), all in the Pali district. Further north-east microliths have been found on sand-dunes surrounding freshwater lakes at Budha Pushkar (Allchin, Hegde and Goudie, 1972) and Hokhra (Allchin and Goudie, 1974) not far from the town of Ajmer.

In eastern Rajasthan, the Mesolithic phase is even better known, especially in the Mewar region. In the districts of Udaipur, Chitorgarh, Bhilwara, Tonk and Ajmer, some sixty microlithic sites have been discovered, largely on elevated rocky surfaces where suitable raw materials, like chert and chalcedony, were available as nodules in limestone outcrops. On these sites, artifactual material mostly consists of waste products with only rare blades and microliths. It is clear that here we are dealing with workshop sites where prehistoric hunters manufactured their tools probably during intervals of hunting expeditions, taking advantage of the easily available raw materials. They took the finished tools to their camp sites and left the waste products behind. Sites on river banks, such as Nimbahera on the Kadmali, south of Chittorgarh, show a higher proportion of finished tools and were, therefore, probably used as temporary camps (Misra, 1967).

A few camp sites of a more permanent nature have also been discovered. The best known of these sites is Bagor (74° 23′ E: 25°21′N) in the Bhilwara district (Misra, 1973). The site is located on a prominent sand-dune overlooking the Kothari river. Horizontal excavations during three seasons between 1968 and 1970 have yielded extensive living-floors and have yielded a variety of cultural materials. Estimates made on the basis of the location of trenches on the mound suggest that about 6,000 sq.m must have been occupied during the Mesolithic period. Radiocarbon dates suggest a duration of nearly 3,000 years for the settlement. The ecological setting of the site probably helps to explain the unusually large size and duration of the settlement. Bagor is located in the midst of an extensive undulating rocky plain. Cultivation is confined to narrow alluvial strips, and the rocky tracts are covered with grass, shrubs and a Savannah type vegetation of *khejri* (*Prosopis cineraria*), *palas* (*Butea frondosa*) and *khajur* (*Phoenix sylvestris*) trees. Wild animals, like blackbuck (*Antilope cervicapra* Linn.), *nilgai* (*Boselaphus tragocamelus* Pallas), fox, jackal, rabbit and a variety of game birds are still available in the area. Several millennia ago, when both human and animal demands on vegetation were far less, the vegetation cover must have been denser and wild-life more plentiful. Close to the site is a large depression, now partially strengthened by an artificial embankment which retains water for the greater part of the year and is a source of irrigation. There is ample geomorphological evidence to show that this depression is a remnant of the old bed of the Kothari river, and that it existed before the Mesolithic occupation of the site. It must, therefore, have been the source of water for the inhabitants and a major attraction for establishing the settlement.

The habitation deposit at Bagor is 1.50 m thick and consists throughout of wind-borne sand. Three phases of occupation can be recognized. Phase I represented by a deposit of 50 to 80 cm is purely Mesolithic. Here, the microlithic industry and animal remains are most profuse. Structural remains consist of extensive stone-paved floors and occasionally circular alignments of stones with diameters of 3 to 5 m, the latter probably representing outlines of huts or windbreaks. Animal bones, mostly broken, split open and charred, and microliths and their debris lay thickly scattered on these floors. Small areas—40 to 70 cm across—tightly packed with pebbles and full of bones probably represent butchering-places. Numerous stone hammers with tell-tale marks of bruising were presumably used for breaking and splitting open animal bones and for manufacturing stone implements. Occasional shallow querns and rubbers must have been used for the preparation of plant foods. The dead were disposed of during this time as well as during phase II within the habitation areas. A single burial from this phase belongs to an adult person. The body was laid in an extended position with head to the west, and no grave goods were provided.

In phase II, the essential elements of phase I including the microlithic industry, animal bones and stone-paved floors persist, but there is a slow decline in the quantity of stone tools and animal bones. Instead, new elements, such as pottery, copper tools and stone beads, make their appearance, suggesting contact between Bagor hunter-gatherers and farming settlements in the region (Misra, 1970). Pottery from this phase is handmade and ill-baked though the shapes are quite sophisticated. Decoration on it consists of incised and applique designs (Misra, 1973). Copper objects, all found in association with burials, include three triangular barbed arrowheads with two holes near the base for fastening the arrowhead to the shaft, one spearhead and one awl-like rod (Misra, 1970). Arrow-heads show close similarity to specimens of the same class from many Harappan sites and to later examples from the Minoan Bronze Age (Misra, 1970). The only example of this class of arrow-head from a non-Harappan Chalcolithic site in India comes from the recent excavation in Indore in Madhya Pradesh (Dr V.S. Wakankar personal communication). Three human burials from this phase were all laid in a flexed position and were richly provided with grave goods in the form of clay pots (originally no doubt containing food and water), copper tools (probably belonging to the deceased), pieces of meat (now surviving as bare bones) and in one case a terracotta spindle whorl and a necklace of thirty-six stones and bone-beads (Misra, 1972).

In phase III, microliths and animal bones further decline in quantity. Besides, this phase has also given plentiful wheel-made plain pottery, two iron arrowheads and stray pieces of iron, glass beads and floors paved with brickbats and occasionally dressed stone. It appears that the site was reoccupied in early historical times and in this process later materials got mixed up with microliths and animal bones of the earlier two phases.

The most characteristic and abundant cultural material at the site is the stone industry. This is exceptionally rich, comprising several hundred thousand worked pieces. It is richest in phase I and gradually declines in later phases. The industry is made up of quartz, chert and chalcedony and consists essentially of microliths, the flake and core tools being very scarce. The microlithic industry is essentially of a geometric character comprising blunted back and obliquely truncated blades, crescents, isosceles and scalene triangles, trapezes and *petit tranchets*, the last more typical than at any other Indian site.

The main evidence for the subsistence pattern of the settlement comes from animal bones (Thomas, 1975). Of the 2,266 identified bones, 72.29 per cent come from phase I, 19.06 % from phase II, and only 2.65 per cent from phase III. The following animals are represented: sheep/goat (*Ovis orientalis vignei*/*Capra hircus aegagrus* Linn.), humped cattle (*Bos indicus* Linn.), pig (*Sus scrofa cristatus* Wagner), buffalo (*Bubalus bubalis* Linn.), blackbuck (*Antilope cervicapra* Linn.), *chinkara* (*Gazella gazella* Pallas), *chital* (*Axis axis* Erxleben), *sambar* (*Cervus unicolor* Kerr), hare (*Lepus nigricois* F. Cuvier), fox (*Vulpes* sp.) and mongoose (*Herpestes* sp.). In all phases, sheep or goat bones account for between 60 and 80% of the bone material. It must, however, be pointed out that the trochlear bones from which most of the identifications have been made cannot always be separated with certainty in the case of sheep or goat on the one hand and blackbuck on the other. The Bagor economy appears to have been based from the outset, on a combination of hunting-gathering and stock-raising. In phase II, the appearance of new material traits, such as copper tools, pottery, ornaments of stone-beads and richly furnished graves and also the decline in the quantity of microliths and animal bones all indicate an increased economic stability and prosperity, and by inference imply a greater reliance on stock-raising. The presence of some perforated circular stones, ethnographically documented for their use as weights of digging-sticks, might suggest a practice of rudimentary agriculture. The presence of tortoise and fish bones in all phases shows the exploitation of aquatic resources as well.

Five radiocarbon determinations, all obtained from charred bone, are known from the site. Three of them come from phase I and two from phase II. These are as follows: phase I : TF—786. 6,245 ± 200 (6430 ± 200) = 4480 B.C.; TF—1107. 5,620 ± 125 (5,785 ± 130) = 3,835 B.C.; TF—1012. 5090 ± 85 (5,235 ± 90) = 3285 B.C., phase II: TF—1009. 4,585± 105 (4,715±105) = 2765 B.C.; TF—1005 and TF—1009. 4,585 ± 105 (4,060 ± 90)= 2110 B.C.

Since no dates are available from the

lowermost levels of phase I, it may not be unreasonable to put the beginning of this phase around 5000 B.C. The beginning of phase II can be put around the middle of the second millennium B.C., because archaeological evidence does not justify expecting copper tools and pottery before that date in this area. The end of this phase cannot be dated in the absence of radiocarbon determinations. Phase III, as has been pointed out earlier, may be a post-Mesolithic occupation, and may be as late as the first half of the first millennium of the Christian Era.

PROBLEMS OF PALAEO-ECOLOGY AND PALAEO-CLIMATE

In recent years, there has been considerable effort at reconstructing the palaeo-ecology and palaeo-climate of western India during the late Quaternary, and the evidence up to the beginning of 1972 was critically reviewed by Misra (1973). The most significant evidence has come from the palynological work of Singh (1971) in the salt lakes of Sambhar, Didwana and Lunkaransar in western Rajasthan. The climatic sequence worked out by Singh is briefly as follows:

Phase I : Before 8000 B.C. This phase, represented by wind-borne sand deposits at the base of lake sediments, was characterized by an arid climate.

Phase II : Pollen zone A: circa 8000 B.C. —circa 7500 B.C. This phase is represented by the first sedimentation in lakes. On the basis of vegetation, as deduced from the pollen record, Singh believes that rainfall at this time was at least 25 cm more than the present annual precipitation in western Rajasthan.

Phase III : Pollen zone B : circa 7500 B.C.—circa 3000 B.C. A slight decline in rainfall is indicated at the beginning of this phase, but it was not severe enough to substantially alter the ecological pattern established in phase II. A noteworthy feature of this phase is the extraordinary rise in carbonized vegetable remains at all the sites. This rise is accompanied with the appearance of *Cerealia* type pollen. Singh believes that these two phenomena indicate scrub-burning at the hands of man and this practice in turn, was connected with the emergency of primitive slash-and-burn agriculture.

Phase IV : Pollen zone C: circa 3000 B.C.—circa 1000 B.C. This phase can be divided into three sub-phases IVa (c. 3000 B.C.—c. 1800 B.C.), IVb (c. 1800 B.C.—c. 1500 B.C.); IVc (c. 1500 B.C.—c. 1000 B.C.). Phase IVa is characterized by a considerable increase in rainfall, as depicted in the pollen record. According to Singh, the annual average rainfall during this phase may have been in excess by at least 50 cm of the present-day rainfall in the arid belt. This period coincides with the emergence and flourishing of pre-Harappan and Harappan cultures in north-west India, and the increase in rainfall may have been one of the causative factors in the expansion of these cultures.

Though the dating of the Mesolithic cultures of north-west India (except eastern Rajasthan) is at present uncertain, there seems little doubt that most of these cultures must have flourished during the period covered by the palynological sequence in the lakes. During this long period, namely, 7500 B.C. to 1000 B.C. except for two relatively short intervals, viz., 8000 B.C. to 7500 B.C. and 3000 B.C. to 1800 B.C., rainfall appears to have been only marginally higher than at present.

In recent years archaeological and geomorphological studies by Allchin, Hegde and Goudie in Gujarat and western Rajasthan have produced evidence of climatic change in the past. According to these investigators, the active dunes in western India are now confined to the west of the 275 mm isohyet, whereas the fossil dunes extend several hundred kilometres towards the east where the annual rainfall ranges from around 900 mm at Baroda in the south, through 600 mm at Jaipur in the centre to 430 mm at Hissar in the north. From this distribution it follows that the annual rainfall in the zone of fossil dunes has increased by two to four times since the cessation of the dune-building activity.

At some six sites in Gujarat and western Rajasthan where digging has been done, microliths and other cultural materials are invariably found to occur within the body of the dunes at varying depths. This evidence shows that microlithic man lived in Gujarat and Rajasthan when the *dune-building processes were active.* And at these sites, there is little evidence to show any interruption in the dune-building activity during the Mesolithic occupation.

Chalcolithic and Bronze ages

The emergence of settled community way of life based on a food-producing economy in the arid and semi-arid zones of north-west India is geographically very uneven and not easily explicable. Whereas Singh's (1971) palynological evidence from salt lakes of western Rajasthan suggests the beginning of cereal agriculture of slash-and-burn type as early as the seventh millennium B.C., there is no archaeological evidence at all at present to support this hypothesis. This is not all. Whereas regular pre-Harappan or Harappan towns and villages or both are known from Saurashtra, Kutch, southernmost Gujarat, the Ghaggar Valley in northern Rajasthan, and Haryana, not a single pre-Iron Age agricultural settlement is known from the whole of western Rajasthan outside the Ghaggar Valley and in the Gujarat plain. Whereas Singh's palynological evidence shows a considerably wet climate between 3000 B.C. and 1500 B.C., this climatic amelioration did not lead to the appearance of the agricultural way of life in much of the arid and semi-arid zone. Also at the moment, there is no archaeological evidence to suggest that the food-producing way of life emerged independently in this zone; on the contrary, all available evidence indicates that it was introduced from the west, i.e. Sind and Baluchistan.

In Gujarat, a large number of Harappan settlements—both towns and villages—are known from Saurashtra. The most famous of these is the port town of Lothal, located about 90 km south of Ahmedabad (Rao, 1973). Smaller Harappan settlements are known from the estuaries of the Narmada and its tributaries in the Surat and Broach districts. Further south on the Tapti, two chalcolithic settlements, namely Malvan and Jokha, have been excavated. The pottery industries of Malvan show influences from Malwa, Deccan and Saurashtra. The settlers here had also dug a ditch 1.10 m deep and 1.50 m wide perhaps for irrigation (Allchin and Joshi, 1972).

In Kutch, some 17 Harappan settlements have been found. Of them, two, namely Desalpur and Surkotada, have been excavated. The settlement at Surkotada was fortified with mud-bricks and included a citadel and a residential area. Three phases of occupation, namely IA, IB, IC, are distinguished. The earliest occupation was Harappan in character, but certain ceramics show the influence of earlier cultures from Baluchistan and Iran. Besides the typical Harappan features, this phase also gave bone tools, potsherds bearing the Harappan script, *linga*-like objects of unbaked clay and four pot burials. In phase IB, the width of the citadel rampart was reduced from 7 to 6 m and a mud-brick reinforcement was provided for the inner face on the eastern side. Phase IC shows considerable changes. Stone rubble as well as dressed stones were used on a large scale in the construction of the fortification as well as in that of residential units. Though writing on potsherds disappears, new ceramic elements appear. Chief among these are the white-painted black-and-red wares showing affinities with phase IC of Ahar in Mewar. Eight C 14 dates show the duration of this settlement from 2000 B.C. to 1600 B.C. (Joshi, 1972). The sequence at Desalpur is broadly similar to that at Surkotada.

The large number and the large size of the Harappan settlements in Kutch clearly show that climatic and environmental conditions in this area from the end of the third millennium B.C. to the middle of the second millennium B.C. were far more favourable to human occupation than they are today. It is also clear that the Harappan colonization of this area took place from Sind by a land route.

In northern Rajasthan, the valley of the now dried-up Ghaggar river was the scene of the emergence of earliest rural and urban centres in the area. Stein (1942) had discovered a string of such settlements on the Ghaggar in the then Bikaner State and further down in the then Bahawalpur State (where the river is known as the Hakra) as early as the early forties of this century. But in the early fifties, it was the systematic exploration by Ghosh (1952) which led to the discovery of 25 Harappan sites and a large number of later settlements on this river in the Sriganganagar District. One of these sites, namely Kalibangan, has been horizontally excavated by the Archaeological Survey of India over several years. It has brought to light not only a large and fortified Harappan township, but also an earlier and fortified Pre-Harappan settlement (Thapar, 1973, 1975).

There are two mounds at Kalibangan. Whereas both these mounds were occupied during the Harappan times, the Pre-Harappan settlement is known only from the western mound or Kalibangan 1.

This Pre-Harappan settlement was fortified with a mud-brick wall which was initially 1.90 m in width but was later enlarged to almost double the width. The houses were also made of mud-bricks and were provided with underground as well as overground ovens of the *tandoor* type. The pottery of these people, though possessing considerable variety, is thinner and less perfectly baked than the Harappan pottery. Some of the pots are roughened on the outer surface by the application of sand and some have decoration of deeply incised lines on the outer surface as well as on the inner surface.

The Pre-Harappan settlers knew the use of copper for making axes, but also used small stone blades for cutting. Their ornaments included beads of steatite, shell, carnelian, terracotta and copper and bangles of terracotta, shell and copper. The discovery of a terracotta cart with a single-sided hub shows their knowledge of wheeled transport. The most noteworthy finding of the Pre-Harappan culture at Kalibangan is the discovery of a ploughed field. It had a grid pattern of furrows; one set running east-west, had a spacings of 30 cm between adjacent furrows, whereas the second running north-south, had a spacing of 1.90 m. A similar ploughing pattern is in vogue in the area today and the two kinds of furrows are used for sowing two different crops. The antiquity of this practice can be traced to the Pre-Harappan times. The discovery of barley grains testifies to its cultivation. A series of radio-carbon dates puts the duration of this culture between 2300 B.C. and 2100 B.C.

The Harappan culture appeared at the site while the Pre-Harappan settlement was still a functioning entity. For some time, the two cultures coexisted, but slowly the Harappan element proved more dominant and completely replaced the Pre-Harappan culture.

The Harappan occupation took place over the earlier Pre-Harappan settlement as well as over a new area to the east (KLB—2). The Harappan settlement comprised two parts as at other Harappan cities—a citadel to the west and a residential area to the east. The city was planned on the well-known Indus chess-board pattern. It was fortified with a mud-brick wall. The houses were made of mud bricks, though burnt bricks were used in drains and wells. The citadel was also fortified with a mud-brick wall, and the structures which have largely disappeared were constructed on massive mud-brick platforms. On one of these platforms have been found several fire altars consisting of shallow pits with a cylindrical or rectangular clay bricks inside. They certainly had a religious function.

The Harappans also cultivated barley, but we do not know about other grains. They domesticated cattle, buffalo, pig, elephant, ass and camel, and hunted *barasingha* and rhinoceros. They buried their dead in a cemetery away from the settlement. Usually, the dead were buried in oblong pits in an extended position with head to the north, and a number of pots (originally, no doubt, containing food and water) were placed near the head. The second type of graves consist of circular or oval pits. The third type of graves is rectangular or oval in plan, but, curiously, these have yielded no skeletal remains. There is evidence that the Kalibangan people practised trepanning or skull surgery.

Their material culture was rich and varied. Their pottery was wheel-made, sturdy, well-baked and decorated with painted designs in black over a red surface. Their ornaments included beads and bangles in shell, terracotta, semi-precious stones and faience. They had weights and measures of the Harappan type, carts, metal tools and seals with Harappan writing. A large number of radio-carbon dates show that the Harappan culture here lasted from 2100 B.C. to 1800 B.C.

The presence of a string of Harappan and Pre-Harappan settlements along the Ghaggar from Hanumangarh to the Pakistan border amply shows that the river at this time was regularly flowing and carried enough water to support agriculture for a large population.

In our present state of knowledge, the Harappan culture does not appear to have extended beyond the Ghaggar Valley in Rajasthan. In north-east Rajasthan, the earliest occupation is represented by ochre-coloured pottery (O.C.P.) culture. It is known from many sites, two of which, namely Jodhpura on the Sabi Nadi, 100 km north of Jaipur, and Noh near Bharatpur (*IAR* 1963-64, pp. 29-30, 1964-65, pp. 65-66, 1965-66, pp. 69-70) have been excavated by the State Department of Archaeology and Museums, Rajasthan. Because of the small size of excavations, very little is known of the life of the people at that time. The pottery is wheel-made and has an ochre-coloured wash. It is decorated with incised and less often with painted designs. The fabric and shapes suggest it to be a degenerate version of the Harappan pottery. There are also traces of mud-brick and wattle-and-daub structures. Circumstantial evidence suggests that the makers of O.C.P. were also the authors of copper objects, generally known as Copper Hoards which have been found on the surface. Though no C14 dates are available, archaeological evidence suggests this culture to have flourished in the second half of the second millennium B.C.

The culture which succeeded the O.C.P. is represented by black-and-red wares. Unlike the black-and-red wares of Harappa and Ahar cultures, this pottery bears no decoration. Associated with these wares are coarse red ware and black-slipped ware. Unfortunately, our knowledge of the other aspects of this culture is negligible, again because of very limited excavations.

On the other side of the Aravallis, in Mewar, a well-developed culture flourished in the early second millennium B.C. This culture is known as 'Ahar' after the type site or 'Banas' after the river basin in which it flourished. Some fifty sites of this culture are known in the valleys of the Banas and its tributaries in Udaipur, Chittorgarh, Bhilwara, Ajmer and Tonk districts of Rajasthan (Misra, 1967, 1969). Two of these, namely, Ahar near Udaipur (Sankalia, Deo and Ansari, 1969) and Gilund on the Banas in the Chittorgarh district (*IAR*, 1959-60, pp. 40-45), have been excavated. The Aharians lived in houses made of undressed stones, though at Gilund there is evidence of the use of mud-bricks and baked bricks. The houses had *chulhas* or ovens of the type in vogue in rural India today. They cultivated rice and perhaps other crops also. They reared cattle, sheep, goat and pig. Unlike other contemporary cultures, they made little use of stone blades. Instead, they used metal more commonly and knew the art of smelting copper ores and casting metal objects. Their ceramic industry is rich and varied. Whereas in the earlier stages, there exists in small quantities the Harappan type of pottery, the most distinctive ceramic of Ahar culture is black-and-red ware with decoration of geometric designs in black. Radio-carbon dates put the period of this culture between 2100 B.C. and 1300 B.C.

Recent researches by Suraj Bhan (1972, 1973) and the State Department of Archaeology, Haryana, have thrown valuable light on the early human colonization of the Saraswati, Drishadvati and Upper Yamuna valleys. Till a decade ago, our knowledge of the subject was confined to the discovery of the Harappan culture at Rupar and Bara (*IAR*, 1954-55) in the former Ambala district (and now in the newly created Ropar district). As a result of explorations by Suraj Bhan, nearly 100 Chalcolithic sites have been brought to light in these valleys. Small excavations have been done at Siswal, Mitathal and Daulatpur in the Hissar District. Two large settlements, namely, Banawali in the Hissar District and Bhagwanpura in the Kurukshetra District are now being excavated on a large scale by the State Department of Archaeology, Haryana, and the Archaeological Survey of India, respectively. Consequently, our knowledge of the prehistoric cultural development is confined to the sequence of cultures. The way of life during various periods can be known only after horizontal excavations are completed and published.

The earliest human colonization in Haryana belongs to the Pre-Harappan or Kalibangan I culture which in Haryana has been given the name Siswal A. It is represented by bichrome (black-and-white) painted and incised ceramics of the types known from Kalibangan. This pottery is known from nearly 20 sites, most of which are located on the Drishadvati river. However, the presence of sites on the Saraswati and along a now dried-up channel running parallel to the Yamuna on its western side shows that the whole of Haryana was colonized by the Siswal A people.

The next cultural phase is represented by Siswal B or a late phase of the Pre-Harappan Kalibangan I culture. The pottery of these people is similar to that of Siswal A people. It is sturdier and better made, but lacks variety in types and designs. Some typical Harappan culture types also appear, showing contact between Pre-Harappan and Harappan (Mitathal II A) cultures. Siswal B people lived in mud-brick houses plastered with clay. Their material culture included saddle querns, terracotta cakes, sling balls, chert blades, copper and clay bangles and beads of copper, terracotta and semi-precious stones.

The Siswal B culture is known from over 30 sites most of which are located in the Drishadvati and old Yamuna valleys. However, the distribution of other sites shows that these people had colonized the whole of Haryana right up to the Siwalik foothills. On the basis of radiocarbon dates from Rajasthan, the duration of the Siswal culture can be put from 2300 to 2000 B. C.

The next stage in cultural evolution belongs to the full-fledged Harappan culture which, at present, is known only from a dozen sites. Of these, Mitathal on the old Yamuna course, Rakhigarhi on the Drishadvati and Banawali on the Saraswati river all in the Hissar District represent the urban centres. Each of these sites has twin mounds—the citadel and the residential areas—so typical of the Harappan city-planning. Current excavations at Banawali show that both the citadel and the residential areas were fortified, and the two were connected by a gate in the intervening defence wall. The houses were made of mud-bricks but baked bricks were used in wells and drains. At all these sites, the material culture includes typical Harappan elements, such as black painted sturdy pottery, chert blades, steatite seals, cubical stone weights, terracotta cakes, beads and bangles of paste and faience, terracotta wheeled toys and animal figurines and copper objects. Unlike in north Rajasthan, the Siswal B cultural elements survive right through the Harappan culture, showing that the Harappans coexisted peacefully with their Siswal predecessors and were slowly able to assimilate them in their own culture. The Harappan culture probably lasted from 2000 B.C. to 1700 B.C.

The final phase of Chalcolithic or Bronze Age in Haryana is represented by the late Harappa (Mitathal II B) culture. Sites of this culture are relatively few and are confined to the middle and upper reaches of the Saraswati and Drishadvati valleys. The absence of this culture in northern Rajasthan and southern Haryana suggests that the lower courses of the Saraswati and the Drishadvati were already drying up, perhaps owing to hydrological changes in the courses of the rivers.

In this culture, the classical Harappan pottery with shapes similar to those of the goblet, beaker, perforated jar, handled saucepan, etc., either become very rare or disappear completely. Other shapes, like dish-on-stand and storage jar, undergo modification in form. The pottery shows a general decline in fabric, manufacturing skill and surface treatment. Certain types and designs of Cemetery H culture pottery are also seen in the Late Harappan pottery at Mitathal and other sites. Similarly, the Late Harappan pottery shows close similarity to the ochre-coloured pottery of the Ganga-Yamuna Doab. The discovery of Copper Hoard objects at Mitathal, Bahadarabad and Saipai in association with the late Harappan and O.C.P. cultures strengthens the belief that the Copper Hoards belong to the late Harappan or O.C.P cultures. The rarity of the Late Harappan, O.C.P. and Copper Hoard sites in Haryana and the Punjab and their abundance in western Uttar Pradesh clearly shows that towards the end of the Harappan culture, the focus of human habitation shifted from the Indo-Gangetic Divide to the Ganga-Yamuna Doab, most probably owing to the increased desiccation caused either by changes in river courses, or in climate or both.

Though Suraj Bhan estimated the duration of the Late Harappan culture from 1700 B.C. to 1500 B.C., the recent discovery of the absence of any gap between the Harappan culture and the P.G.W. culture at Bhagwanpura in the Kurukshetra District in Haryana suggests the possibility that the culture may have endured in this region till the end of the second millennium B.C.

Emergence of Iron age

The emergence of iron technology and the consequent expansion of human colonization in northern Rajasthan, the Indo-Gangetic Divide and the Ganga-Yamuna Doab are associated with the Painted Grey Ware (P.G.W.) culture. The authors of this culture used a fine, thin grey pottery painted with black geometric designs. This pottery is totally different from the Late Harappan pottery in fabric, shapes, decorative patterns and baking technique, and is not even remotely derived from the latter. The Painted-Grey-Ware people lived in mud-houses, cultivated wheat and rice and kept cattle, sheep, goat and horse. They had no knowledge of town-planning, the use of kiln-baked bricks and writing. Their culture was essentially rural and its appearance marks a loss of the Harappan urban tradition. The P.G.W. culture is associated with the Mahabharata period.

A number of Painted-Grey-Ware sites have been found in the Ghaggar Valley in the Sriganganagar District of Rajasthan. But these sites never occur over the older Harappan mounds and, therefore, show a clear chronological gap and break in human habitation between the Harappan culture and the P.G.W. culture. In north-east Rajasthan, numerous sites of this culture are known in Jaipur, Ajmer and Bharatpur districts. The profusion of P.G.-Ware sites in the Ganga-Yamuna Doab testifies to the further shift of human habitation to the east of the previous centre of human colonization.

At Jodhpura, in the Jaipur District and at Noh in the Bharatpur District, the P.G.W. culture overlies the black-and-red ware deposit. Though an iron arrowhead has been found in the black-and-red ware deposit at Noh, the regular use of iron is attested only in the P.G.W. phase. At Jodhpura, furnaces with slag and a nodule of haematite-containing iron ore have been found, providing evidence for the local practice of iron metallurgy. Further south, the P.G. Ware sites extend down to Deoli in the Bundi district on the Khari River. At Chosla the P.G. Wares have been found on a Ahar culture mound. The exact cultural and chronological rela-

Sequence of pre-historic cultures in the arid and semi-arid zones of western India

Chronology (years before present)	Cultural stage	Gujarat plain	Kutch	Western Rajasthan	North-east Rajasthan	Mewar	Haryana
	N.B.P. Ware	Vadnagar	?	?	Jodhpura, Noh		Ropar
2,500	P.G. Ware	?	?	Ghaggar Valley	Jodhpura, Noh	Many sites in Ajmer and Bundi districts	Bhagwanpura
3,000	Black-and-Red Ware	?	?	?	Jodhpura, Noh		
	O.C.P & copper Hoards	?	?	Khurda, Dt. Nagore	Jodhpura, Noh Nandlalpura	?	
3,700	Late Harappan	?	Surkotada IC	?		Ahara-culture	Mitathal
	Harappan culture	?	Many sites Surkotada, Desalpur, etc.	Ghaggar Valley	?	?	Siswal and Mitathal Banawali, Rakhigarhi Siswal & other sites
4,100	Pre-Harappan culture	?	?	Ghaggar Valley	?	?	
4,500	Mesolithic	Extensive occupation Langunaj, Akhaj, Devnimori, Pavagarh, etc.	Limited surface evidence	Many sites, Tilwara, Budha Pushkar etc; extensive occupation	Banara near Jaipur	Extensive and thick occupation Bagor and other sites	?'
12,000	Upper Palaeolithic	Visadi Industry	?	Very limited evidence	?	?	?
20,000 —	Middle Palaeolithic	?	Some implements in central part	Many sites in the Luni and its tributaries, in. Jaisalmer and at Budha Pushkar near Ajmer	?	Very limited evidence	?
50,000 More than 100,000	Lower Palaeolithic	Sabarmati, Mahi and Narmada Valleys	Some implements in central part	Only site is Govindgarh near Ajmer	Bhangarh on Sanwan Nadi near Alwar	Extensive and rich evidence in Chambal, Bana and other Valleys	?

tionship between Ahar and P.G.W. cultures can be deciphered only after excavation at sites like Chosla.

The radio-carbon dates available from Noh and several other sites do not take the antiquity of P.G. Wares earlier than 800 B.C. But the discovery of P.G. Ware at Bhagwanpura immediately over and, in fact, in association with the Harappan culture hold out the possibility of an earlier beginning of these wares.

At all the sites of this culture the P.G. Ware deposits are invariably succeeded by the deposits of the Northern Black Polished (N.B.P.) Wares. This was probably evolved from the P.G. Ware towards the end of the sixth century B.C. and saw its development and diffusion during the Mauryan times. This is a thin, very well-baked and lustrous pottery and marks a high point in the evolution of Indian ceramic technology. The N.B.P. period witnessed the emergence of urbanization in the entire Ganga Valley. From now onwards, we enter the period when recorded history began. In the Ghaggar Valley there is no evidence of N.B.P. culture. The area seems to have been abandoned after the P.G.W. period. After a gap of several centuries, new settlements appeared there during the Kushana period in the early centuries of the Christian era.

In the whole of the semi-arid and arid zone of western Rajasthan (leaving aside the Ghaggar Valley in the extreme north) there is no evidence of agricultural settlements of Chalcolithic Age. The same is true in respect of the Gujarat plain. Indeed, there is no evidence in this region of such settlements even in the late first millennium B.C. when the Iron Age had already commenced in north-east Rajasthan and the Indo-Ganga plains. The absence of such settlements cannot be explained owing to the lack of archaeological work. In spite of extensive and systematic explorations, this vast region remains a big blank on the Chalcolithic map of India.

It is difficult to reconcile this archaeological evidence—or rather the lack of it—with the climatic picture worked out by Singh on the basis of palynological history of saline lakes in western Rajasthan. While palynology shows a very humid climate in the semi-arid and arid zone from C. 3000 B.C. to C. 1500 B.C., no agricultural settlements developed in the Luni Valley or on the shores of the then freshwater lakes. The Ghaggar Valley, where such settlements did develop, is a few hundred kilometres to the north of these lakes. If the climatic changes reflected in the palynological record of these lakes affected the emergence of settled life in the Ghaggar Valley, surely their impact should have been felt nearer home as well.

Recently, Raikes (1968), on the basis of the study of bore holes on the Ghaggar bed, has revived the old theory that the Yamuna flowed in the past in the Ghaggar bed. In fact, his theory is that the Yamuna was alternately captured by the Indus and Ganga systems, and whenever it flowed in the Ghaggar bed, settlements flourished along that river.

Suraj Bhan (1972) has traced an old course of the Yamuna over a length of 180 km from Indri in the north-east to Tigrana in the south-west in Haryana. He has also located nearly twenty Pre-Harappan and Harappan sites along the banks of this old channel. Two other channels between this course and the present-day Yamuna course testify to the gradual eastward shifting of the Yamuna course. The Late Harappan and P.G. Ware sites have been found along these channels. It, therefore, appears very likely that the development of early farming and urban cultures in the Ghaggar Valley in Rajasthan and in the Saraswati-Drishadvati-Yamuna valleys in Haryana was largely conditioned by hydrological changes rather than by climatic factors.

The chart on facing page gives a broad picture of the evolution of prehistoric cultures in the arid and semi-arid zone of north-west India.

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4

CLIMATIC CHANGES IN THE INDIAN DESERT

GURDIP SINGH

IN the early fifties, great concern was expressed over the reportedly rapid spread of the Rajasthan desert into the hitherto fertile tracts surrounding the region: "Recent topographical surveys show that the great Indian desert of Rajasthan has been spreading outwards in a great convex arc through Ferozepur, Patiala and Agra towards Aligarh and Kasganj at the rate of about half a mile per year for the last 50 years, and is encroaching upon approximately 50 square miles of fertile land every year" (*Report of the Planning Commission of the Government of India in Its First Five-Year Plan*). The claim for the extension of the desert, however, did not find support from the large body of expert opinion, then available, as brought out in the *Proceedings of the Symposium on the Rajputana Desert*, organized by the National Institute of Sciences of India in 1952. Indeed, the meteorological record over the previous 70 years showed no significant change in rainfall, temperature, humidity and wind velocity over the desert areas and, therefore, no plausible case could be made to support the contention of the progressive spread of the Rajasthan desert in recent years as indicated in the report (Pramanik *et al.*, 1952).

DETERIORATION IN DESERT CONDITIONS

Regarding another important question whether the desert conditions had deteriorated gradually over a longer period, there was no precise information available, though Krishnan (1952) was of the opinion: "Desert conditions must have gradually set in well after man appeared, possibly in geologically subrecent times." It was generally held that the desert conditions had deteriorated as compared with conditions obtaining during the period of the Harappan Culture (2300–1750 B.C.) and also to some extent in relation to some later cultures which flourished in north-western India in the early centuries of the Christian Era (Ghosh, 1952). Later on similar views were expressed by Wadia (1960) and Wheeler (1966). However, as the deductions on the nature of the climate during the time of these cultures rested on indirect evidence provided by human artifacts, such as sculptures, drawings and engravings of animals and plants on potsherds and stalactite seals, burnt bricks, animal bones, wood and charcoal remains, the size of major cities and the location of habitation sites with respect to river courses, flooding horizons, the existence of an elaborate drainage system, the occurrence of "gabar bands", the testimony to higher rainfall argued from each of these lines of evidence was cast in doubt by some authors (Raikes and Dyson, 1961; Raikes, 1964; Dales, 1966). According to these authors, there was not appreciable climatic change in the South Asian area during the last four to five thousand years and that it was not the climatic change but the flooding of the rivers, with a major flood about once in 140 years that weakened the power structure of the Indus Valley civilization, so that the more remote areas to the north became vulnerable to outside pressures (Dales, 1966; Raikes and Dyson. 1961).

Following the decline of the Harappan culture, 1750 B.C. (Agrawal *et al.*, 1964), the Bainted Gray Ware culture is said to have established itself in the area about 1000 B.C. According to Ghosh (1952), its establishment was associated with a shaky water-supply, together with an impoverishment of the land. Later on, it is shown that the Rangmahal culture, which occupied the same region during the early centuries of the Christian Era, had an adequate water-supply and that there was probably a partial resuscitation of the river system until its decay in the seventh or eighth century when the population seems to have turned to a nomadic existence (Ghosh, 1952). Nevertheless, Ghosh mentions that according to the *Mahabharata*, generally placed in the early centuries of the Christian Era, Bikaner was arid during that period.

The evidence on climatic conditions for the subsequent periods is rather sketchy. From the eighth century to the twelfth century, Junah (now Chotun) is said to have had 12,000 habitable dwellings (Todd, 1829), when the same place is now no more than a small village of 200 huts. Yet, according to Nazim (1931), Mahmud of Ghazni, during the course of his invasion of north-western India in the eleventh century, had to make elaborate arrangements for water-supply to cross the desert from Multan to Somnath.

Until the advent of palynological studies of the lake deposits in the Rajasthan desert in the late sixties, the evidence of Late Quaternary climatic history had suffered greatly from a lack of continuity in its chronological sequence. The archaeological and geological records were marked by long gaps, for which there was no evidence, one way or another. This lack of continuity had obviously resulted from the nature of the sites investigated where the records could not survive in an unbroken order.

The observations made by the present author, and his associates, based on the stratigraphy, radiocarbon dating and pollen analysis of the salt-lake deposits at Sambhar, Lunkaransar and Didwana in western Rajasthan, and a freshwater lake deposit at Pushkar in the Aravalli Hills, have been published and the reader is referred to them for fuller details (Singh, 1967, 1969, 1971; Singh *et al.*, 1972; Singh *et al.*, 1974). These studies were carried out in conjunction with a general survey of the modern pollen fall-out from the vegetation of north-western India (Singh *et al.*, 1973). This survey was conducted from 114 modern pollen spectra from sixty-four different sites spread all over north-western India with a view to finding modern analogues of the changing plant assemblages in the fossil pollen records, so that deductions could be made about the palaeoclimates in the region. The studies also encompassed the pollen analysis of the dated archaeological soil samples from the Indus Valley site at Kalibangan in northern Rajasthan (Singh, 1971; Singh *et al.*, 1974).

In this article, attention is focussed on the evidence pertaining to the Late-Quaternary desertification in the stratigraphical records. So far, two periods of desertification, described here as Desertification I and II, are discernible in the Late-Quaternary sequence (Figure). Of these, the one dating from before 10,000 B.P. is by far the severest. In the earlier epochs, palaeobotanical evidence indicating the tropical rainforest conditions in Rajasthan is available from the Eocene period, some 60 million years ago (Kaul, 1951; Lakhanpal and Bose, 1951; Bose, 1952), but this period is followed by a great gap in the information lasting until the Late-Quaternary period.

Desertification I. At each of the salt lakes worked out in western Rajasthan, it is seen that lacustrine deposits overlie the beds of aeolian sand, and represent the fossil dune fields dating from before 10,000 B.P. (Singh, 1971; Singh *et al.*, 1972, 1974). In the section (Singh *et al.*, 1974. pp. 480, 485, 487), the dune fields extend inwards from the margins of the encircling sand-dunes and lie directly below a sequence of laminated clays. At lower levels, the sand grades into a *kankar* pan resulting from leaching as well as from the cementing of sand particles by calcium carbonate. At Sambhar, the presence of thin layers of cemented sandstone in the otherwise loose sand-bed perhaps indicates some very short-term inundations. This feature is, however, not seen at the other two sites. From the combined stratigraphical evidence from all the three sites, it is suggested that sometime before about 10,000 B.P. (Figure), extremely severe arid conditions with dry winds prevailed in western Rajasthan (cf. Allchin and Goudie, 1971), with the result that extensive dunes were deposited and they led to the choking of valleys with sand to give shape to closed inland basins, such as at Sambhar, Lunkaransar and Didwana. No firm date has been assigned to the beginning of this period of desertification, but its upper limit coincides with the Late Weichseliam/Falandrian boundary (8,000 B.C.) of western Europe. The closest parallel situations to this phase of aridity in Rajasthan is seen in Iran where the pre-Holocene arid phase has been equated with the last full-glacial times (Van Zeist, 1967). The desertification, 10,000 years ago, in Rajasthan, is one of the several pieces of evidence that now disprove the long-standing theory that ice ages in the north necessarily correspond with abundant rain in the tropics. It is now accepted that a fall in temperature during the last ice age, in fact, led to a decreased rainfall.

The latter part of Desertification I, in Rajasthan, was contemporaneous with a warming trend which was already in progress 14,000-15,000 years ago in the Kashmir Himalayas, following the last full-glacial (Singh and Agrawal, 1976). But since there was a time-lag between the actual rise in temperatures and the warming of the ocean surface, the reversal in the trend, in terms of increased precipitation, was probably delayed. Nevertheless, as pointed out earlier, some short-term inundations of the basin of the Sambhar Lake did take place occasionally, as evidenced by the cemented sandstone layers intercalated in the aeolian sand-bed, suggesting some increase in precipitation before the final infilling of the lake basin about 10,000 B.P.

Sub-humid interval. The infilling of the lake basins with fresh water about 10,000 B.P. (8,000 B.C.), in Rajasthan, finally brought Desertification I to a close (Figure). The lakes once filled remained fresh for 6,000-7,000 years (Singh *et al.*, 1974). In view of the fact that there was no intercalation of sand layers in the laminated lacustrine clays deposited during this period, it was inferred that the sand-dunes remained stabilized throughout. The vegetation, as evidenced by the pollen record, first comprised an openland steppe

Figure

BROAD TRENDS OF DESERTIFICATION IN THE LATE-QUATERNARY HISTORY OF CLIMATE IN RAJASTHAN

DESERTIFICATION II LAKES START TO DRY AND TURN SALT MESOPHYTIC VEGETATION DISAPPEARS	SLIGHT AMELIORATIONS OF CLIMATE
AMELIORATION OF CLIMATE SAND-DUNES STABILIZED PRESENT SALT-LAKE BASINS FILLED WITH FRESHWATER VEGETATION MORE MESOPHYTIC THAN THE PRESENT	
DESERTIFICATION I SAND-DUNES ACTIVE	

which was rich in grasses, *Artemisia* and sedges, and poor in salt-tolerant halophytic species. *Artemisia*, *Typha angustata*, *Mimosa rubicaulis* and *Oldenlandia*, which now grow under areas of comparatively high average annual rainfall (above 500 mm), appear to have flourished in the contemporary semi-arid belt (250–500 mm average annual rainfall), whereas the first two taxa had encroached upon even as far as the arid belt (100–250 mm average annual rainfall). Both facts suggest that a general westward shift of the rainfall belts had taken place. From this situation it was estimated that there was at least 250 mm more of rain than that at present in the arid belt (Singh *et al.*, 1974). Similar increase in precipitation over those witnessed in Rajasthan during the early Holocene are now well documented from several other parts of the world (e.g., Kershaw, 1974). In Queensland, Australia, for instance, as much as four- to five-fold increase in precipitation is estimated to have taken place during the Holocene as compared with that during the full-glacial times (Kershaw, 1974).

Except for the period from 9,500-5,000 B.P. (7,500-3,000 B.C.), when the rainfall was marginally diminished (but remained above that of the present day) as evidenced by the rise in the number of halophytes, the period from 10,000-4,000 B.P. (8,000-2,000 B.C.) enjoyed a substantially greater rainfall than the present in both the arid and semi-arid zones. The increase in swamp vegetation and the intensification of tree and other vegetation cover inland together with the maxima of all mesophytic elements (e.g., *Syzygium*, *Mimosa rubicaulis*, etc.) between 5,000 and 3,800 B.P. (3,000 and 1,800 B.C.) at Sambhar, indicate a period of optimum rainfall.

Desertification II. Following the above amelioration of the climate, there was a short relatively dry time about 3,800-3,500 B.P. (1,800-1500 B.C.) during which all the mesophytic species disappeared at Sambhar and the disappearance is correlated with the decline of the Indus Valley culture in north-western India (Singh, 1971). From 3,500-3,000 B.P. (1,500-1,000 B.C.) there was some recovery in the vegetation, but none of the mesophytic species occurring earlier returned to Sambhar, showing that the recovery was not a substantial one. Thus Desertification II in Rajasthan may be suggested to have started around 4,000 B.P. (Fig.). The first evidence of the onset of this phase is seen in the breakdown of the laminations in the lake sediments at Lunkaransar, in the arid belt, about 4,000 B.P. (2,000 B.C.), together with the lack of preservation of pollen above that level. At Sambhar, in the semi-arid belt, the evidence comes from the final disappearance of mesophytic elements from the flora about 3,800 B.P. (1,800 B.C.) even though the breakdown in the laminations and also the lack of pollen preservation in the lake sediments did not take place until 3,000 B.P. (1,000 B.C.) at this site. It has been suggested earlier that this onset of aridity in Rajasthan was fatal to the Indus Valley culture and that it greatly contributed to its downfall (Singh, 1971).

The question, however, arises as to what led to this desertification? Was it due to the activities of man or was it natural, or both? These questions have been discussed at length earlier by Singh *et al.* (1974) and the force of arguments, on the whole, favoured the idea of a natural climatic change for the region. The palynological studies have shown quite clearly that the tree vegetation in Rajasthan increased hand in hand with the expansion of the Neolithic and Chalcolithic cultures despite the fact that the burning of vegetation (as part of primitive agricultural practices) had gone on over the previous four millennia in the region. The increase in vegetation along with the spread of human cultures could not have gone on without an extraordinarily favourable climate prevailing during that period. Later on, the fact that the lakes dried out, together with a decline in the mesophytic plant species showed that the onset of aridity was independent of human influence. According to Eriksson (1959), during the latter part of the post-glacial period, Rajputana (including a part of Rajasthan) has become more arid and the amount of wind-borne sand resulting from dune instability has increased. Recently, a sample from a pollen zone (Stage g) in a pollen diagram from Toshmaidan (3,120 m a.s.l.—Singh, 1963), indicating the falling temperatures in the latter half of the post-glacial period in the Kashmir Valley, gave a date of 2790—160 B.P. (PRL-2 B) (Singh and Agrawal, 1976), showing that the fall in temperatures must have preceded this date. Thus a case can be made that the onset of Desertification II in Rajasthan was probably synchronous with the lowering of temperatures in north-western India.

The course of minor oscillations of climate since the second desertification began needs further elucidation. The pollen diagram from Pushkar, in the Aravalli Hills, which holds the pollen records for this interval, has not yet been dated by means of radiocarbon. As a result, the dates assigned to the various levels in the Pushkar pollen profile are still very tentative.

At Pushkar, a mesophytic community, consisting of *Anogeissus pendula*, gives way to a vegetation dominated by desert species, such as *Calligonum*, *Maytenus*, *Ephedra*, *Capparis* and *Prosopis cineraria* during a period which has been correlated with Desertification II in western Rajasthan. Later on, this trend was reversed at a date estimated around A.D. 400 with the result that the desert species declined, giving place to *Anogeissus pendula*, *Ficus* and a number of other mesophytic species which have lasted to the present day (Singh *et al.*, 1974). However, as the salt-lakes in western Rajasthan remained saline and mostly as dry as today since the beginning of Desertification II, it is likely that the reversal in the desertification trend seen in the Aravallis around A.D. 400 was rather small. This is supported by the archaeological evidence from sites occupied by the Rangmahal culture during the early centuries of the Christian Era. According to Ghosh (1952), there was only a partial resuscitation of the river system during the period of occupation by this culture. At Lunkaransar, there is evidence for some renewed preservation of pollen in the upper layers, but the plant assemblage, as deduced from the pollen record in these layers, is much the same as that of today, again showing that the climatic change since the beginning of the second desertification phase has been rather insignificant.

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5

PALYNOLOGICAL EVIDENCE ON CLIMATIC CHANGES IN JAISALMER BASIN, RAJASTHAN

N. G. LUKOSE

WESTERN Rajasthan is a paleo-shelf, bounded by the Aravalli range to the east, by the Indus geosyncline dissected by the basement ridges to the south and by the Delhi-Lahore ridge to the north. A transverse basement ridge, the Mari-Jaisalmer arch separated the basin configuration of this part. The sediments that were deposited in the tectonic depressions NE and SW of the ridge include the Trans-Aravalli Vindyans. These sediments are classified into the arenaceous Jodhpur group, the calcareous Bilara group and arenaceous Nagaur group. The Jodhpur group of rocks are deposited in sublittoral intertidal zone. The arenaceous to calcareous facies change suggests epineritic to infraneritic environment. The presence of stromatolites in the Bilara Formation indicates that the water column would not have been greater than 100 metre deep (Pareek, 1975).

The studies carried out on the sedimentary structures (Khan and Mukhopadhyay, 1971-72; Mukhopadhyay and Sinha, 1973-74) indicate the prevalence of a general westward palaeo-current flow direction, indicating the easterly source area. The sedimentological analysis (Mukhopadhyay, 1970-73) indicates the sandstones of Girbhankar (Jodhpur Formation) and Nagaur Formation were deposited in deltaic-intertidal to beach environment and shallow marine environment. Contemporaneous with this sedimentation the Randa and Birmania Formations were deposited near Birmania in the Jaisalmer basin. The Birmania Formation is considered homotaxial with the Bilara Formation of Bap-Bikaner area. Freshwater environments must have prevailed during the deposition of the Birmania Formation, whereas the marine environment prevailed during the deposition of the Bilara group of rocks. The prevalence of oxidation environment is indicated during the deposition of the overlying Nagaur Group, as evidenced from red beds. From the marked similarity between the Salt Range Saline Series of Pakistan and the rock formations of the Trans-Aravalli Vindhyans, the existence of a wide and long basin is inferred. It is believed that most of western Rajasthan remained as land during the period from the early Palaeozoic to the beginning of the Mesozoic. A large part of Sind, Baluchistan, Rajasthan and Cutch was covered by the sea during the Middle Jurassic period. The Lathi Formation (Liassic) has a wide extension from near Barmer to Jaisalmer and Lathi. The Jurassic sediments are represented by the lower arenaceous Lathi Formation, the middle Calcareous Jaisalmer Formation and the upper Baisakhi and Dedesir Formations. The Neocomian sediments are represented by the Pariwar Formation, indicating shallow marine to brackish and continental environments. The Aptian and the Albian to Turonian sediments are represented by Abur Goru Parh Formations, indicating a shallow marine environment. The overlying Ranikot, Laki and Kirthar Formations (Paleocene-Middle Eocene) are mainly deposited under a shallow marine environment, except for small regressive facies in Ranikot. This time-gap did not exist in Cutch and in the Salt Range where continuous deposition is evidenced (Pareek, 1975). During the Sub-Recent period, the Shumar Formation got deposited under the freshwater environment. It commences with glauconitic clay base, grades into gravelly sands, sandstones, limestone and aeolian sand with reworked Eocene fossils, suggesting arid to desert conditions. The general sub-surface stratigraphy and lithology of the Jaisalmer basin are given in Table 1.

Table 1. General sub-surface stratigraphy, Jaisalmer basin

Group	System	Series	Stage	Formation	Member	Lithology
Quaternary		Recent			Dune sand	
					α	Sand and clay
					β	Limestone and calcareous sandstone
		Sub-Recent		Shumar	γ	Sandstone and variegated clay
					δ	Alternating variegated clay and coarse-grained sandstone and glauconitic clay
T						UNCONFORMITY
E		Middle Eocene	Lutetian	Kirthar	Bakhri	Clay
					Tibba	Limestone
R					Habib	Clay
	Eocene				Rahi	Limestone
T		Lower Eocene	Ypresian		Ghazij	Shale
						Limestone
I				Laki		Shale
A					Dunghan	Limestone
						Marl
R	Palaeocene					Limestone
Y						Marl/clay/shale
				Ranikot		DISCONFORMITY
						Limestone
						Clay and marl, sandstone
						Clay sandstone
M						UNCONFORMITY
E			Coniacian	Parh		Marl
S			Turonian			Clay/marl/limestone
						Clay/marl/I
						Clay and marl
O		Upper				Limestone
Z		Cretaceous				
O			Cenomanian	Upper Goru		Marl and silty shale/clay
						Silty and sandy clay, clay with siltstone intercalation
I	Cretaceous					Arenaceous shales
C			Albian	Lower		Sand

Table 1. (*Contd*)

Group	System	Series	Stage	Formation	Member	Lithology
				Goru		Shale-siltstone intercalations
C R E T A C E O U S						Argillaceous bed sand/sandstone fine-grained with shale intercalations
	Lower Cretaceous					Sandy clay/shale with limestone intercalations shale/grey-greenish clay with siltstone intercalations
						Shale grey greenish clay with siltstone intercalations
						Argillaceous sandstone and shale intercalations and siltstone intercalations Sandy shales-glauconitic
						Sandstone fine to medium and shales
						Argillaceous sandstone and black carbonaceous clay
						Sandstone coarse-grained and argillaceous
			Neocomian	Pariwar		Sandstone with shale intercalations Sandstone and silty shale, black shale
						Grey to brown silty clay shale, sandstone argillaceous
Mesozoic						Shale and argillaceous standstone intercalations Sandstone/clay/siltstone intercalation
		Upper Jurassic	Portlandian	Baisakhi Bedesir		Sandstone argillaceous Sandstone and carbonaceous shales
			Kimmeridgian			Sandstone medium to coarse and argillaceous
						Sandstone fine to medium and hard
						Silty clay/silty shale golden oolite
						Microcrystalline and oolitic limestone

Table 1. (*Contd*)

Group	System	Series	Stage	Formation	Member	Lithology
Mesozoic	Jurassic		Oxfordian Callovian	Jaisalmer	Limestone member	Sandstone with shale streaks
						Coquinoidal limestone/ sandstone with alternating band of shale
					Shale member	Shale dark grey, with alternations of sandstones
						Limestone (oolitic) with siltstone
						Shale dark grey. Coquinoidal sandstone with carbonaceous material
						Claystone variegated, grey-greenish maroon, brick-red
						Sandstone greyish white, coarse-grained, calcareous
						Sandstone cream-coloured medium to coarse-grained.
	Lower Jurassic	Liassic	Lathi			Claystone chocolate brown with sandstone intercalations
						Sandstone greyish, white coarse to medium-grained with claystone streaks
						Siltstone, grey, brown to chocolate brown, yellowish brown and pink
Palaeozoic	Triassic			Pre-Lathi		Claystone grey, greenish brown
						Sandstone brown, grey with variegated clay/shale streaks
	Permian					Sandstone coarse-grained with rhyolite and quartzite chips
						Siltstone sandstone non-calcareous with carbonaceous shale bands
						Shale-sandstone alternation

In western Rajasthan after the Early Palaeozoic transgression, the first transgression of the sea in the Jaisalmer basin is represented by the marine Permian sediments, as evidenced in the Shumarwali Talai and Bhuana wells drilled by the Oil and Natural Gas Commission during the explorative drilling for hydrocarbons. Regressive facies occur to the top of the Permian sediments. The Triassic sediments are represented by the basal regressive beds, middle transgressive beds and upper regressive beds. The Liassic sediments are represented by the continental Lathi Formation. This is overlain by carbonate rocks of the Jaisalmer Formation, representing Callovo-Oxfordian age, and the shaly Baisakhi Formation (Kimmeridgian), representing marine transgression. The overlying Bedesir Formation (Tithonian) represents the regressive phase, succeeded by the shallow marine-brackish and continental Pariwar Formation of the Neocomian Age. The next major transgressive facies are represented by the Habur Formation (Aptian), the Goru Formation (Albian to Cenomanian) and the Parh Formation Turonian to Coniacian in age. The regression of the sea and the break in sedimentation is observed during the Post-Coniacian to Modstrichian periods. A part of the Lower Paleocene beds of the Ranikot Formation represent a freshwater environment. The last and major transgression of the sea in the Jaisalmer basin is during the middle Paleocene and this transgressive facies are represented by the upper beds of the Ranikot Formation (Middle Paleocene), the Laki Formation (Upper Paleocene to Lower Eocene) and the Kirthar Formation (Middle Eocene). At the close of the Lutetian, the sea receded completely from the Jaisalmer basin and the area remained as land during the Upper Eocene, Oligocene, Miocene periods till the beginning of the Sub-Recent Shumar sedimentation. The paleo-environments of deposition of the Jaisalmer basin sediments are given in Table 2.

Table 2. Paleo-environment, Jaisalmer basin sediments

Time		Rock unit		Rock unit	Paleo-environment
Group	System	Series	Stage	Formation	
Quaternary		Sub-Recent		Shumar	Continental
				Unconformity	
Tertiary	Eo cene	Middle	Lutetian	Kirthar	
		Lower	Ypresian	Laki	Shallow marine
	Paleocene	Upper			
		Middle		Ranikot	
		Lower			
					Fresh water
	Cretaceous			Unconformity	
		Upper	Coniacian		
			Turonian	Parh	
					Shallow marine
			Cenomanian	Goru	
			Albian		
			Aptian	Habur	
		Lower	Neocomian	Pariwar	Shallow marine-brackish and continental

Table 2. (*Contd*)

MESOZOIC	JURASSIC	Upper	Tithonian Kimmeridgian	Bedesir Baisakhi	Regressive
			Oxfordian	Jaisalmer	
		Middle	Callovian		Shallow marine
		Lower	Liassic	Lathi	Continental
	Triassic				Regressive Shallow marine Regressive
PALAEOZOIC	Permian				Regressive Shallow marine
				Unconformity Birmania Unconformity Randa Unconformity	
			Malani	Igneous	Suite

Table 3. Paleo-climate and Paleo-environment, Jaisalmer basin

System	Series	Paleo-basin environment	Terrestrial flora (relative)	Paleo-climate
Sub-Recent		Continental	Insignificant. Pteridophytic spores practically nil	Arid
	Lutetian	Shallow marine	Poor flora and pteridophytic element in particular	Semi-arid
Eocene	Ypresian			
Paleocene		Shallow marine Freshwater (regressive facies)	Considerable reduction in total land flora and significant reduction in peteridophytic elements	Semi-humid
	Coniacian	Shallow marine		
	Turonian			
Cretaceous	Cenomanian Albian Aptian	Shallow marine	Luxuriant and pteridophytic elements plenty	Warm-humid
	Neocomian	Shallow marine continental		
	Upper (Tithonian Kimmeridgian)	Continental and shallow marine		Warm and temperate
Jurassic			Luxuriant	
	Middle (Callovo-Oxfordian)	Shallow marine		
	Liassic	Continental		
Triassic		Continental Shallow marine Continental	As compared with Permian, reduction is observed in terrestrial flora	Temperate
Permian		Continental Shallow marine	Luxuriant	Temperate and cool

The time and the various factors that led to the origin of the Rajasthan desert, popularly known as the Thar Desert extending between latitudes 24°35′ North and 30°10′ North, and between longitudes 69°30′ East and 76°East, covering about 2,00,000 sq. km of western India have remained obscure. The various factors which contributed to the formation of this desert, as postulated by various authors are: (1) that this region lies along the well-known northern desert belt, and the aridity and the large diurnal variations of temperature disintegrate the rocks and help to form sand which is distributed by the action of winds (Krishnan, 1956); (2) that owing to a long-continued and extreme degree of aridity of the region, combined with the sand-drifting action of the south-western monsoon sweeps through Rajputana for several months of the year without precipitating any part of their combined moisture (Wadia, 1957); (3) that this region is located on the leeward side of the Aravallis and, therefore, the precipitation is small; (4) that it is located in the trade-wind belt where the air is moving towards the Equator, causing warm and increased capacity to hold moisture which causes high evaporation and transpiration loss resulting in aridity, (5) that the rising of the Himalayas and the lowering of the Aravallis have changed the course of the moisture-bearing winds (Sen, 1964); (6) that owing to the impoverishment of and the consequent deepening of the subsoil water-table, there took place the diversion of the Himalayan waters (Rode, 1964).

The weather is the condition of atmosphere at any time or place and is expressed by the combination of elements, primarily the temperature, precipitation and humidity, wind and air pressure. They are the ingredients, out of which seasons, weather and climatic types are formed. The weather of any place is the sum total of its atmospheric conditions, namely temperature, winds, moisture and precipitation for a short period whereas the climate is a composite variety of day-to-day weather conditions. The climate varies regionally over the earth and with time, and differs from place to place, whereas weather varies from day to day. The cause of several climatic elements varies from place to place and season to season, resulting in the season being hot or cold in some places, wet in another place and dry in still another place. These variations are due to climatic controls, namely latitude, distribution of land and sea (water), winds and air masses, altitude, mountain barriers high-and-low-pressure centres, ocean currents and various kinds of storms. These controls, acting with various intensities and combinations, produce the changes in temperature, precipitation and evaporation which, in turn, give rise to varieties of weather and climate. The natural vegetation in different parts of the world has all the time not existed in its present form. It had never been static, but as the climate changed in the past, the vegetation also changed. Modifications and varieties within the climatically induced larger plant communities are usually the result of secondary factors, chiefly the soil and biotic elements and they are associated with exposure, drainage, climatic, and human exploitation. Thus whereas the climatic control is of primary importance in plant growth, development and distribution, the edaphic control is secondary. However, soil and climate are not completely independent factors, as soil characters are greatly influenced by climate and natural vegetation. Still in the soils, there are many local variations, which are the result of non-climatic factors, such as the parent soil material and the bedrock drainage conditions, and the slope. As such, the soil may vary almost from one spot to another, and as a result, produce local variations in vegetational cover. In addition to climatic and edaphic factors, there is the biotic factor. Thus overgrazing can change the native vegetation of a region. Other biotic factors are associated with pollinating insects, the relation between hosts and parasites, and the obligatory food dependency. Since the plants are immobile they must adapt themselves to their environment and thus a plant is a captive of its environment. Similarly, unlike animals, the plants do not generate heat. As a consequence their very existence is greatly influenced by the air and soil temperature and thus for every plant species, there are three critical temperatures, namely a lower and an upper limit, beyond which it cannot survive, and the third, an optimum temperature at which it vigorously flourishes (Finch *et al.*, 1957).

The palynological assemblage of the Jaisalmer basin, the Permo-Triassic sediments (Tikku *et al.*, 1976; Lukose and Misra, 1976), the Lathi Formation Liassic, the Jaisalmer Formation Callovo-Oxfordian (Lukose, 1971) suggest the prevalence of a cool to temperate climate and luxuriant terrestrial vegetation near and around the shore of the basin of deposition. The palynology of the Baisakhi-Bedesir Formation-Upper Jurassic, and the Habur, Pariwar and Goru Formations and the Lower Cretaceous (Neocomian to Cenomanian) indicate that during the deposition of these sediments, the vegetation near and around the basin had been luxuriant, and the warm and humid climate prevailed, as evidenced by the presence of a high percentage of pteridophytic spores in the sediments. However, a gradual but steady decrease in the sporomorph, in general, and the pteridophytic elements, in particular, have been observed in the overlying Upper Cretaceous, Paleocene, Lower and Middle Eocene sediments and practically devoid of sporomorph in the Sub-Recent Shumar Formation (Lukose, 1974).

Figure 1 shows the percentage of terrestrial and non-terrestrial elements calculated from the total sporomorph count obtained from the sub-surface Goru, Parh, Ranikot, Laki, Kirthar and Shumar Formation, of Jaisalmer basin corresponding to Albian-Canomanian, Turonian-Conician, Paleocene, Yprecian, Lutetian and Sub-Recent periods. Out of 44% of the terrestrial sporomorph, 15% are of pteridophytic spores in Albian-Cenomanian sediments. The total percentage of terrestrial sporomorph is almost reduced to 1/6 in the Upper Cretaceous sediments with a conspicuous reduction in pteridophytic spores in relation to its percentage in Albian-Cenomanian sediments. Whereas the total sporomorph percentage remained unchanged in relation to the Upper Cretaceous sediments, the percentage of pteridophytic elements has been considerably reduced to 0 5% in the Ranikot (Paleocene) sediments. The total percentage of terrestrial sporomorph has been reduced in the overlying Laki and Kirthar (Eocene) sediments with a progressive reduction in pteridophytic spores to a meagre 0 3 per cent. As regards the Sub-Recent Shumar Formation, the presence of sporomorph is very meagre and practically the sediments are devoid of spores and pollen-grains.

Unless nearby shore areas of a sedimentary basin had luxuriant vegetational cover consistent with time and space, the sporomorph representation in a given quantity of sediment will be insignificant in quantity, if the basin preservational environment has otherwise remained good. The occurrence of lignite and halite reported by Sinha *et al.* (1973) within the Tertiary sediments further confirms the prevalence of severe and continued aridity. It may be argued that the quantitative and qualitative differences in spore and pollen content in the sediments belonging to the same or different lithozones or different geological periods may be due to unfavourable edaphic factors or geochemical conditions of the basin during or after the deposition or both. In such an event, the sporomorph recovered from the respective sediments will show a bad state of preservation. But the occurrence of well-preserved sporomorph in the various sedimentary sequences indicates the existence of favourable geochemical and other basin conditions during the deposition of the various sedimentary sequences. The progressively diminishing quantity of pteridophytic spores and other terrestrial pollen-grains from one period to another in the post-Cenomanian sediments could be attributed to the prevalence of adverse climatic

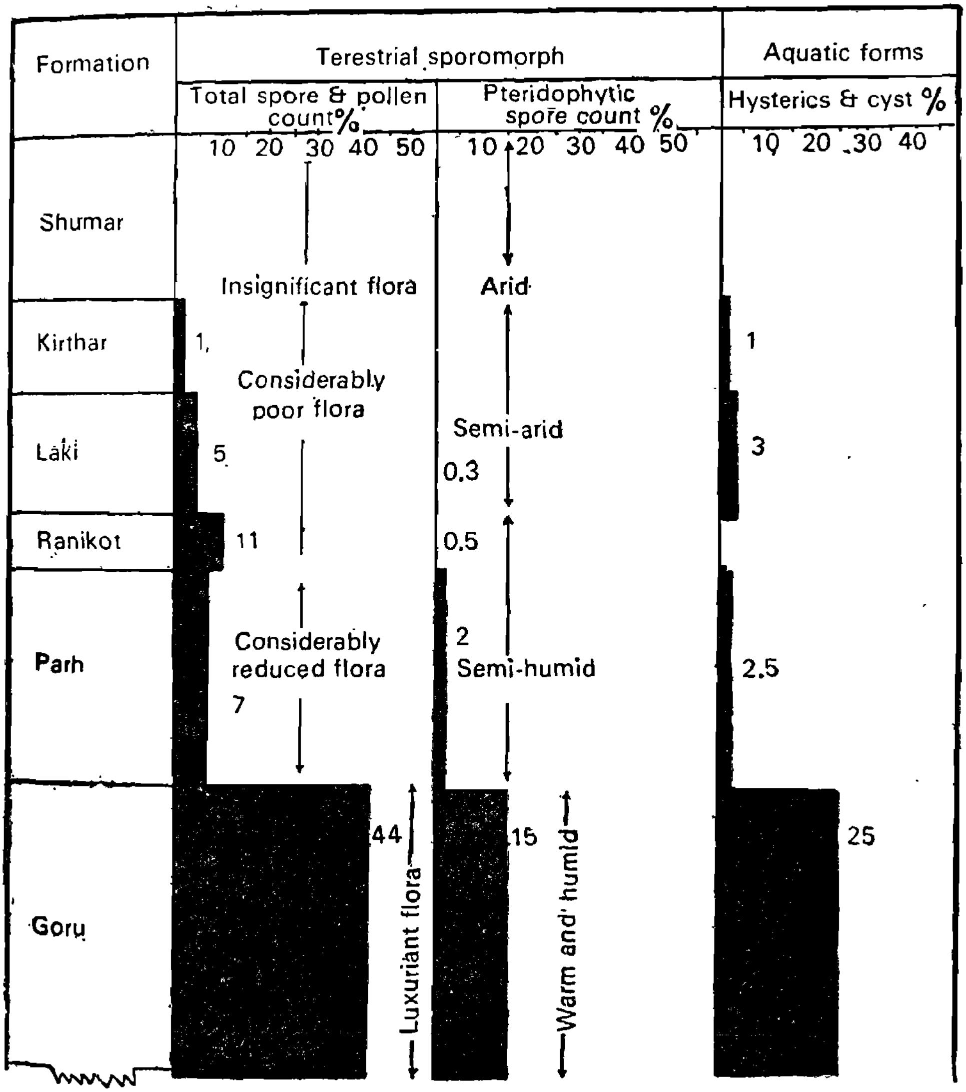

Fig. 1. Paleoclimate

conditions or changes in climate from one period to another which, in turn, caused a gradual but progressive destruction of the natural vegetation consistent with time and space.

Even though the transgression and regression of the sea took place a number of times during the Permo-Lower Cretaceous period, yet the sedimentation process continued during these periods with no significant break, with the result that the basin remained submerged under water. Throughout the Permo-Lower Cretaceous periods, this water body controlled the climate of the vast area near and around the basin. There is little doubt that the Rajasthan desert was occupied by sea, and marine communication existed from Kutch to western Rajasthan. However, the microfossil evidence indicates the prevalence of unstable basin environment and frequent fluctuations in the sea-level during the Neocomian and Cenomanian periods and the regression of the sea from the basin during the Post-Coniacian period and a break in sedimentation during the Upper Cretaceous period corresponding to the Coniacian to Masdstrichian over a period of 20 million years. Possibly, the unstable basin environment, and later the withdrawal of the vast water body due to regression, and the upliftment of land must have affected adversely the climate owing to the change in one of the major climatic factors, namely the distribution of land and sea, which in turn, had altered the wind and air mass to make changes in temperature, precipitation and evaporation. This change might have resulted in less and less humid conditions over a period of 20 million years, which ultimately effected the destruction of the land flora near and around the basin. Lakhanpal and Bose (1951), and Lakhanpal (1964) reported the occurrence of numerous angiosperm leaves and fruit impressions of Guttiferae, *Mesua* and *Garcinia* from Fuller's Earth sediments. Kaul (1951) reported the impression of palm fruit *Cocos sahnii* from Kapurdi. The prolific occurrence of the fossils belonging to the rain-forest and coastal vegetation in the above Eocene sediments further supports a large-scale destruction of such flora during the Eocene period.

During the Paleocene, the basin submerged under the transgressed sea and it remained submerged till the close of the Lutetian time, but under the unstable and frequently fluctuating basin environment. The last major regression of the sea from western Rajasthan is during the close of the Lutetian and the basin uplifted and remained without sedimentation for a period of 35-40 million years. This regression had once again disturbed the climatic control (land-water distribution), resulting in changes in temperature, precipitation and evaporation, wind and air mass. The prevalence of the disturbed climatic control over a period of 35 million years resulted in semi-arid to arid climate during the Post-Lutetian period, causing the destruction of whatever land flora remained during the Paleocene-Middle Eocene transgressive period. However, after the regression of the sea, some flora still may have flourished in isolation near and around the left-out lakes and other water bodies. Further, it is not possible to rule out the prevalence of the wet period or cycle during the Middle Eocene to the Sub-Recent unconformity period. But there is no sedimentary evidence to support this statement, as it would have been quite insignificant in time and space.

In the geological history of the Jaisalmer basin, the last sedimentation cycle is represented by the Sub-Recent Shumar Formation. The palynological evidence suggests that these sediments were deposited under the non-marine environment and the continuance of aridity and scanty vegetation near and around the basin while the Shumar was being deposited.

The spores and pollen grains are very meagre in the Shumar sediments and the pteridophytic elements are practically nil. The presence of organic matter in the sediments, in general, is very poor as compared with that in the underlying Eocene sediments. Further in these sediments, fair distribution of reworked Eocene Foraminifera and the occurrence of variegated clays were observed. All these factors suggest weathering, erosion and the reworking of sediments, besides the prevalence of aridity. Had a prolific land flora thrived over the uplifed land during the Post-Eocene unconformity, plenty of organic matter, plant microfossils and megafossils would have occurred in the Shumar sediments owing to the submergence of this flora during the deposition of the Sub-Recent Shumar Formation.

Favourable climatic variation for a number of years in succession may very well bring up a good vegetational cover in isolation. But it may perish in the next spell of aridity, even though a few of them may adapt themselves to a certain extent and survive immediate destruction. As such, the flora will not sustain itself, if unfavourable arid climate prevails for long periods. A favourable climate consistent with time and space allows the growth, development, and natural replenishment of the flora. The luxuriant flora establishes the microclimate, maintains atmospheric humidity, increases soil productivity besides stopping soil erosion and other principal sand-forming activities, namely weathering exfoliation and the crumbling of rocks.

The palaeoclimate and the palaeoenvironment of the deposition of the sediments in the Jaisalmer basin, as evidenced from the palynology, is summarized in Table 3.

The palynological evidence of the Jaisalmer basin suggests the prevalence of a cool temperate to temperate warm climate and the existence of luxuriant land vegetation during the Permo-Jurassic period; a warm and humid climate and luxuriant flora during the Lower Cretaceous period, semihumid climate and reduced land flora during the Upper Cretaceous-Paleocene period, semi-arid climate during the Early Eocene and the arid climate during the Sub-Recent times while the Shumar sediments are being deposited,

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6

A CLIMATIC ANALYSIS OF THE ARID ZONE OF NORTH-WESTERN INDIA

A. KRISHNAN

ARID zones are characterized by sparse and highly variable precipitation, extreme variation of diurnal and annual temperature and high evaporation. The crop or pasture production in this zone should, therefore, aim at using the available water most efficiently. Thus a detailed study of various climatic factors in these regions is extremely important. The object of this chapter is, therefore, to study in detail the climatic patterns of the arid zone in north-western India, especially with regard to changes and trends with a view to getting a better insight into the occurrence of the desertification process, if any.

DELIMITATION OF THE ARID ZONE OF INDIA

Pramanik, Hariharan and Ghosh (1952) classified the climates of various places in and around Rajasthan by using isopleths of De-martonne's indices of aridity. The climatic classification of India and the delineation of the arid zones have been carried out by Carter (1954), Subramanyam (1956), Subramanyam *et al.* (1965), Shanbagh (1956) and Bhatia (1957). But these studies were based on the data of only meteorological observatories, for which long-period normals were available. Since the network of such stations is not dense enough for carrying out the detailed delineation of the arid areas in the country, Krishnan (1968a) classified the arid and semi-arid zones of India by utilizing not only the normals of meteorological observatories but also those of the provincial raingauge stations which are considerably numerous. Thornthwaite's (1948) moisture indices were worked out for each of these stations and the areas with moisture index values less than 40 were delineated as the arid zone. A study made by Krishnan and Shankarnarayan (1964) revealed that the climatic classifications made by using Emberger and Thornthwaite's methods agree well with the distribution of vegetation in these zones.

The State-wise areas of the arid zone in India and the percentage of the total area in the arid zone in the country are presented in Table 1.

Table 1. State-wise areas of the arid zone in India

State	Area under the arid zone (km^2)	Percentage of the total arid zone in India
Rajasthan	1,96,150	62
Gujarat	62,180	20
Punjab	14,510	5
Haryana	12,840	4
Maharashtra	1,290	0·4
Karnataka	8,570	3
Andhra Pradesh	21,550	7
Total area	3,17,090	
Jammu and Kashmir*	70,300	—

*Cold arid zone

Thus the area in the arid zone in north-western India constitutes almost 90 per cent of the total arid zone in the country (excluding the cold desert of Ladakh in the Jammu and Kashmir State).

Rajasthan

Krishnan (1968b) has furnished information on the district-wise areas of the arid zone in Rajasthan. The boundary between the arid and the semi-arid zones in Rajasthan cuts across the Jalore and Pali districts, goes roughly along the boundaries of the Ajmer and Nagaur districts. The districts in Rajasthan lying wholly in the arid zone are Ganganagar, Bikaner, Jaisalmer, Barmer, Jodhpur and Churu. The districts lying partly in the arid zone and partly in the semi-arid zone are as follows: (The percentage of area falling in the arid zone is given in brackets). Nagaur (96), Jalore (88), Jhunjhunu (69), Sikar (65), Pali (48) and Ajmer (9).

Punjab-Haryana

To the north of Rajasthan, the demarcation line of the arid zone intersects the Mahendragarh and Hissar districts of Haryana and the Sangrur, Bhatinda and Ferozepur districts of the Punjab State. The percentages of the arid zone in the above-mentioned districts are as follows: Ferozepur (77), Bhatinda (88), Sangrur (8), Hissar (90), and Mahendragarh (9).

Gujarat

To the South ofRajasthan, the boundary of the arid zone passes through the following districts (arid area expressed as percentage in brackets): Banaskantha (18), Mehsana (7), Ahmedabad (6), Surendranagar (29), Rajkot (6), Jamnagar (80) and Junagadh (20). In Gujarat, the only district which is wholly included in the arid zone is Kutch.

PECULIARITY OF THE INDIAN ARID ZONE

Krishnan (1968a) presented data on the moisture retained in or on the surface of the land in each 10° longitude zone of the belt contained between 30° and 40° latitude. These data indicate that there is extremely poor moisture retention in this latitude belt in the longitudinal range from 20°W to 70°E. However, there is a sharp increase in moisture detention, more so from 80°E longitude onwards towards the east.

The moisture-detention values are uniformly high in the longitudinal range 80°–120°E. Thus the comparatively little coverage of the arid zone in the belt 20°–30° N and the occurrence of the arid zone right in the region of the lowest pressure during the main rainy season are peculiar to our longitudinal range. This may be mainly ascribed to the large circulation changes owing to the Asiatic monsoon. Further, the intertropical convergence zone lies only within 3°–10° N latitude in the Pacific Ocean up to 18° latitude in Africa and up to 30°N latitude in India and South-east Asia. In view of the above-mentioned peculiarities in the circulation, the Indian arid zone falls in a peculiar category (Krishnan, 1973).

Though much rainfall is not received in this desert, atmospheric humidity is usually fairly high and is comparable with that of places with higher rainfall in the semi-arid and sub-humid zones, as shown in Table 2 (Krishnan, 1968a).

Thus there is hardly any difference in the actual humidity values. Not only in the surface level, but also in the upper levels, the humidity conditions in the Indian arid zone are high. For instance, the precipitable water vapour in grammes over Jodhpur is almost of the same magnitude as over the humid parts of the country, as can be seen from the following data.

	July	August	September
Jodhpur	5.5	5.1	4.3
Nagpur	5.5	5.4	4.7
Bombay	6.2	6.0	5.3
Trivandrum	4.6	4.4	4.5

There is little difference in respect of the dewpoint depression between New Delhi (semi-arid) and Jodhpur (arid) in May, both at 850 mb and at 700 mb. In July, at the 850 mb level, the humidity values at both the stations are nearly the same, whereas at 700 mb level, the dewpoint

Table 2. Rainfall and vapour pressure at selected stations in the arid, semi-arid and sub-humid zones of India

		Barmer (arid)	Jodhpur (arid)	Kotah (semi-arid)	Indore (sub-humid)	Bhopal (sub-humid)
Mean vapour pressure (mb)	July	28 7	27·9	28·7	26·6	27·1
	August	28·1	28 0	28 7	25 9	27 0
Mean annual rainfall (mm)		310	380	941	1053	1209

depression is lower at New Delhi. This lower depression of the dewpoint should be expected, since a more humid air mass prevails over that region at that height. But the order of humidity at 1.5-km and 3-km levels at Jodhpur is the same.

It, therefore, becomes clear that the Indian arid zone does not get adequate rainfall in spite of the prevalence of high humidity and the availability of a large quantity of precipitable water.

CLIMATOLOGICAL FEATURES IN THE ARID ZONE OF NORTH-WESTERN INDIA

Rainfall pattern

An analysis of the isohyet map of the arid regions of north-western India indicates that the mean annual rainfall varies from 100 mm in the north-western sector of the Jaisalmer district to 450 mm in the eastern boundary of the arid zone in Rajasthan. It varies from less than 300 mm to 500 mm in the arid zone of Gujarat and from 200 to 450 mm in the Haryana-Punjab region. The general decreasing gradient is from the south-east to the north-west. The year-to-year variability, represented by the coefficient of variation, is very high in the western parts of the arid zone of the Rajasthan and Gujarat States. It varies from less than 40 per cent in the Sikar and Jhunjhunu districts to more than 70 per cent in western Jaisalmer and in the Barmer district. Apart from the high variability of rainfall, there is considerable skewness in the distribution also.

The lowest mean values of less than 300 mm are noticed in respect of Barmer, Jaisalmer, Bikaner and Ganganagar. In the case of all stations, the data in respect of which were examined, except Hissar, the mean values are less than the median values which can be expected on 50 per cent of the occasions. In contrast, the skewness is to the right in the case of Hissar.

In view of the skewness in the distribution pattern of rainfall, a knowledge of the percentage frequency distribution of rainfall, based on the data collected over a large number of years becomes extremely important. Accordingly, the frequency distribution of rainfall data of several stations for the period 1901–1970 were analysed and the decile rainfall values corresponding to 10 per cent, 20 per cent .... 90 per cent probabilities were worked out for all stations.

The analyses revealed that once in 10 years, the annual rainfall of the entire arid zone of north-western India can be less than 200 mm, except for Jhunjhunu, Hissar, Sikar and Pali. For Jaisalmer, probability value is only 66 mm. When we consider 20 per cent probability (viz. The deficit pattern expected once in 5 years), the annual rainfall is less than 200 mm for Jaisalmer, Barmer, Bikaner, Ganganagar, Jodhpur and Nagaur. For Jaisalmer, this value is even less than 100 mm. The median values represented by 50 per cent frequency values are invariably less than the mean values, thereby confirming the skewness in the distribution.

Rainfall years of high surplus (flood years) are common in Jaisalmer, Barmer, Jalore, Bikaner and Jodhpur with less of rainfall. Rainfall years of large deficit (drought years) are more frequent in Barmer and Jaisalmer districts, with the percentage frequency values exceeding 20 per cent. Years with a large deficiency in rainfall started occurring more frequently during the decade 1961–1970 in Rajasthan and Gujarat.

In the Sikar and Jhunjhunu districts of Rajasthan, and in the arid zone of the Haryana and Punjab States, the frequencies of both flood years and drought years are very much less.

As regards the seasonal distribution, the main rainy season is from June to September. In Gujarat as well as in southern and central Rajasthan, the contribution of the period from June to September to the annual rainfall varies from 90 to 95 per cent. In view of the winter rainfall contributing from 9 to 12 per cent to the total annual precipitation, the monsoonal contribution is of the order of 78 per cent in the Punjab and 80 to 85 per cent in Haryana and northern Rajasthan.

GENERAL CLIMATIC FEATURES OF THE ARID ZONE OF NORTH-WESTERN INDIA

During winter, clear skies, fine weather and low humidity, large diurnal variations of temperature, and light north-easterly winds are the features of weather. These features are changed only when western disturbances pass over the region and cloudy conditions and sometimes even rain may occur. Winter rainfall is 7 to 12 per cent in the arid zone of the Punjab and Haryana States, 3 to 6 per cent in Rajasthan and is negligible in the arid zone of Gujarat. The southern regions get rain when the secondary of the main disturbances, which move across the Punjab hills, occur over Rajasthan or northern Gujarat. Western disturbances bring in their wake cold waves, so that frosts frequently occur in the northern portion of the north-western Indian arid zone. For instance, a study of the frosts at Bikaner indicates that the period during which frosts are common is from 18th December to 22nd January and the frosts can occur continually for more than 20 days. Such severe winters were found to have occurred in five years out of sixteen years, when the weather data were studied, showing a probability of roughly one frost year in three years. In the severest winter, forty consecutive days of frost had occurred (Krishnan and Thanvi, 1973).

Both the normal values of maximum and minimum temperatures during this season follow roughly the latitudinal pattern. The least value is in respect of Ganganagar. In exceptional years, temperature in the region can be as low as -4.4°C. Frosts can occur at all the stations. The means of the lowest minimum screen temperatures in the individual years are less than 4°C in respect of Phalodi, Jaisalmer, Ganganagar, Bikaner and Hissar, thereby showing that frosts frequently occur at these stations. This is an important feature which should be taken into account while planning the afforestation programmes for stabilizing dunes and doing crop-planning. The mean diurnal variation during the season varies from 14° to 16°C. The winter is very dry. The mean values of vapour pressure are less than 10 mb. The relative humidity, however, is high, especially in the morning owing to very low air temperature.

In summer heating takes place earlier in the southern regions than in the northern regions. The high-pressure system during winter is replaced by a low-pressure area, with a trough extending up to Chhota Nagpur. The desert in north-western India becomes the seat of the greatest heat in the country. May and June are the hottest months of the year. During these months, dry and hot dust-raising winds, popularly known as "loo" and dust storms (*andhi*) occur very frequently. The sandy soil of the area, the scantiness of rainfall due to which the soil is not compacted, the occurrence of steep pressure gradients and super adiabatic lapse rates of temperatures between the surface and the air are the main causes of these convective phenomena.

The mean maximum temperature during summer is 40°C, except in Bhuj, where it is slightly lower because of coastal effects. The mean of the highest temperatures recorded at various stations during each individual year falls in the range of 44° to 45°C. The highest temperatures recorded in the region are, however, in the range of 48° to 50°C.

The values of vapour pressure during summer are higher than those in winter. However, the actual values of relative humidity are lower in summer than those in winter owing to the very high temperatures that occur during summer. The values of vapour pressure in the region vary from 9 to 18 mb, but may suddenly increase in certain areas to more than 20 to 25 mb in the region during the 3rd or 4th week of May.

Though the onset of the south-westerly monsoon takes place by the 1st of June in the southern tip of the country, it occurs in the north-western Indian arid zone only by the last week of June to the first week of July.

The low-pressure area over western Rajasthan during the monsoon months is not of great depth, and circulation becomes anticyclonic at the higher levels. Further, at elevations of 1 to 3 kilometres, dry continental wind blows from Iran and Afghanistan, and it, in turn, prevents the ascending of the seasonal current and the formation of massive clouds. Only when the westward-moving monsoon depressions reach Rajasthan, a large volume of deep and moist monsoonal air is brought in, the development of weather takes place and well-distributed rainfall occurs. Since the monsoon depressions recurve and turn towards the north after reaching Madhya Pradesh, rainfall generally does not occur in the Indian desert. Only in those years when a few depressions move right across the desert, heavy rainfall occurs in the desert. But it is rare. Thus the direction of the movement of the monsoon depressions is one of the important factors in the decrease of precipitation in the arid zone of India. The persistence of the axis of the monsoon trough over the region also causes precipitation in specified locations of the region.

The normal maximum temperature during the monsoon exceeds 35°C, except in Bhuj, where a somewhat lower temperature occurs during the season owing to the blowing of cool equatorial maritime (Em) airmass during most of the season. The values for Ganganagar and Bikaner are higher because of the occurrence of more frequent incursions of drier and hotter north-westerly dry continental airmasses at these stations. The normal minimum temperatures during this season are even slightly higher than those of the summer season. Thus the mean diurnal variation during the season is the least, varying from 7.4°C at Bhuj to 11.4°C at Bikaner.

The values of vapour pressure during the monsoon exceed 25 mb and the values of relative humidity range from 75 to 80 per cent in the mornings and 50 to 60 per cent in the afternoons at all stations, except Bikaner and Ganganagar where the values are slightly lower.

After the withdrawal of the south-westerly monsoon, dry and fairly warm weather prevails till the end of October. This weather is usually referred to as the 'second summer'. An anticyclonic circulation tends to establish itself over north-western India. The values of vapour pressure fall during this season and are comparable with values during the early summer.

During the post-monsoon season, the maximum temperature varies from 32.1°C in Hissar to 33.9°C at Bhuj, and follows roughly the latitudinal pattern. The same pattern holds good for the minimum temperature also. The highest diurnal variation in temperature is noticed during this season, and it ranges from 14.9°C in Barmer to 19.2°C in Ganganagar. The values of vapour pressure vary from 10 to 16 mb, which are similar to those of the early summer.

The mean evaporation during summer exceeds 12 mm per day at the arid-zone stations examined so far. The evaporation values during the monsoon are higher than those during the post-monsoon season.

The least evaporation values of 5-6 mm/day are recorded during the winter season, the annual evaporation works out at 3,437 mm at Jodhpur, 3,195 mm at Pali and 2,809 mm at Ahmedabad.

The seasonal means of potential evapotranspiration at various arid-zone stations computed by using Penman's (1948) method, which takes into account the factors, such as radiation, temperature, wind speed and saturation deficit have been presented in Table 3. The values are applicable to crop surfaces, since an albedo value of 0.25 has been used for computing the energy-balance term.

The potential evapotranspiration during summer varies from 7 to 9 mm/day. During the monsoon, it varies from 5.2 mm at Bhuj to 6-7 mm/day at the northern stations, whereas in winter it is higher at the southern stations than at those in the north. It is noticed that the seasonal means of potential evapotranspiration computed by using Penman's (1948) method are very much less than the pan-evaporation values. A study by Krishnan and Kushwaha (1971) also indicates that under the arid-zone conditions of Jodhpur, Penman's method underestimates the potential values owing to insufficient weightage given to the aerodynamic term which is much more significant in determining the evaporation than the energy-balance term.

It has also been brought out by Krishnan and Kushwaha (1973) that, though as a single factor, the total global radiation has the maximum correlation coefficient of 0.70 with evaporation, the best pair of factors which has the maximum association with evaporation under the arid-zone conditions are the saturation deficit at the maximum-temperature epoch and the daily mean wind speed. These factors explain 83 per cent of the variance in evaporation. The addition of measured total global radiation increases the explained variance only by 5 per cent.

Soil-moisture regime and water-balance pattern

Sand-dunes. In the unstabilized sand-dunes, a sharp discontinuity in moisture content in the layer 1.5 to 2 metres below the soil surface has been observed. Below this layer, the soil moisture reached more than 5 per cent by weight (i.e. the field-capacity value) throughout the year. However, in the stabilized sand-dunes, this feature was not observed and the moisture content was generally found to be less than 1.5 per cent up to a depth of 3 metres with the values increasing as the depth increased. The patterns below this layer were complicated owing to the differential extraction patterns of trees, shrubs and grasses over the stabilized sand-dunes. This feature explains the surer establishment of, and a better growth in, the trees planted on unstabilized dunes.

Sandy plains. A comprehensive experiment on the water balance of the typical native vegetation of the arid zone of north-western India was conducted at the Central Research Farm of the Central Arid-Zone Research Institute, Jodhpur, from 1963 to 1967. Apart from the trees of *Prosopis cineraria* several important species of grasses, e.g. *Dactyloctenium sindicum, Eleusine compressa, Cenchrus*

Table 3. Seasonal means of potential evapotranspiration (mm/day)

	Winter	Summer	Monsoon	Post-monsoon	Annual total (mm)
Bhuj	3·2	7·7	5 2	4·3	1,897
Barmer	2·9	7·7	5·4	3·9	1,858
Jodhpur	2·9	7·9	5 3	3·6	2,063
Jaisalmer	2·5	8·8	5·3	3·8	2,041
Phalodi	2·5	8·8	6 5	4·2	1,771
Bikaner	2·0	7·3	6·3	3·2	1,662
Ganganagar	1·8	6·9	6·4	2·9	1,843
Hissar	1·9	6·8	5·6	3·1	1,616

biflorus, *Cenchrus setigerus*, *Panicum antidotale*, *Aristida adscensionis* and *Cyperus rotundus* were included in the experiment. The soil at the experimental site is sand up to a depth of 15 cm (6% clay content) and sand to loamy sand downwards up to a depth of 200 cm (average clay content 8 per cent). Below this depth there is a *kankar* pan. The soil texture is quite uniform and unaggregated, with constant bulk density of 1.5 g/cm³. During 1963, 1964 and 1965, the rainfall amounted to 156.9, 536.2 and 234.6 mm (the normal annual rainfall at Jodhpur is 366 mm). The monsoon commenced very late in 1963, i.e. on 30 July; very early, in June, in 1964 and very close to the normal date in 1965, i.e. on 4 July.

The water-balance analysis indicates that the period 30 July to 27 September (60 days) accounted for 156 mm of evapotranspiration during the deficient-rainfall year of 1963, whereas the period 10 May to 6 October (150 days) accounted for an evapotranspiration of 321.9 mm and a deep drainage of 34.9 mm during the surplus-rainfall year of 1964. The measured runoff losses were 0.7 mm (0.4 per cent) for 1963 and 125.9 mm (23 per cent) for 1964. The very high runoff loss during 1964 was due to the very high intensity of rainfall between 8 July and 18 August, together with a good antecedent moisture conditions in the soil due to well-distributed rainfall in the season. During the medium-rainfall year of 1965, the period 29 June to 7 October (100 days) had an evapotranspiration loss of 219.5 mm, and a runoff loss of 5 per cent. Thus there was a high variability from year to year in the available growth period for the native vegetation. From the transpiration measurements made during the experiment, it was inferred that the trees of *Prosopis cineraria* extracted moisture not only from large area, but also through the *kankar* zone (Krishnan *et al.*, 1968).

An evapotranspiration model applicable to the native vegetation was evolved from this experiment for predicting the storage of soil moisture under native vegetation during the growing season of the vegetation (Krishnan, 1970). The agreement between the values predicted on the basis of the model and the actually measured values was quite close.

Observations on the comparative soil moisture during the years from 1965 to 1967 in respect of (a) the bare land (free from weeds), (b) the land cropped with *bajra*, and (c) the land with native vegetation indicate that the residual moisture storage after the growing season is maximum in the bare plot, followed by cropped land and then in the grasslands. The last category has moisture below the wilting percentage value. The moisture content of the plot under the native vegetation reached the wilting percentage value in September during the deficit-rainfall years of 1965 and 1966, and in November during the surplus-rainfall year of 1967, though the wilting-point-value was not reached in the bare plot and the cropped land at that time during these years.

The pattern of soil thermal regime

In the arid zone of north-western India, where the predominant soil type is sandy to loamy sand, there are two principal regimes of soil temperature, i.e. (1) the summer pattern when the soil temperature decreases from the surface to a depth of 120 cm during the maximum-temperature epoch and increases up to a depth of 30 cm with a decrease thereafter in respect of the minimum-temperature epoch and (2) the winter pattern when the soil temperature during the maximum-temperature epoch decreases only up to a depth of 30 cm with an increase thereafter and increases continuously during the minimum-temperature epoch from the surface to a depth of 120 cm. The summer pattern lasts from the middle of March to the middle of October, with a few breaks during the rainy spells in the monsoon season, when the winter pattern occurs owing to increased cloudiness and higher moisture content.

The diurnal variation of soil temperatures is present only up to a depth of 30 cm. It ranges from 19° to 28°C at a depth of 1 cm, from 4° to 7°C at a depth of 15 cm and from 0.1° to 0.30°C at a depth of 30 cm. The diurnal variation is considerably reduced during the monsoon season.

In view of the vapour-pressure gradients with the depth on account of changes in soil temperature conditions are favourable to the upward movement of moisture in the vapour phase during the morning hours and are favourable to a downward flow during the afternoon hours throughout the year. From April to the end of October, these gradients are stronger. However, during the monsoon, the downward vapour-pressure gradients in the afternoon are much less than those in other seasons, thereby indicating that the general upward vapour-phase movement of water from the deeper layers to the upper layers during the growing season exists in the arid zone. Thus, to a certain extent, the ill-effects of low water retentivity of the arid-zone soils are reduced.

Though many workers have reported that the annual soil-temperature cycle is well represented by the first harmonic alone, it has been found under the arid-zone conditions of Jodhpur that the first harmonic explains only 69 to 85 per cent. The change in the soil-temperature pattern during the monsoon is well reflected only if the third harmonic is superposed over the sum of the first two harmonics. The amplitude of the first harmonic representation of the annual cycle of soil temperature varies between 4.8°C and 9.1°C at various depths. The amplitude decreases sharply with the higher-order harmonics. In other countries, where there is no monsoon activity, the peak of annual wave of soil temperature is reached in August or so, whereas under the arid-zone conditions of north-western India, the warmest soil near the surface is noticed on the average on 28 June, whereas at a depth of 120 cm the highest temperature occurs on 29 July, i.e. a time-lag of one month (Krishnan and Kushwaha, 1972).

On an average, a soil heat flux of $\pm$ 25 calories/cm^2/week occurs during the period from January to May. But there are weeks having a positive flux of 60 calories/cm^2/week or more or negative fluxes in association with cold spells. The spectacular feature is, however, the occurrence of large oscillations of very much higher order during the monsoon. The range of fluctuation is from +84 to −116 cal/cm^2/week. The weeks of rainfall usually have negative heat fluxes, whereas the intervening dry spells between the two rainy weeks have large positive fluxes. These huge flux values during the rainy season may be partly due to the flow of appreciable heat on account of the mass movement of water and the flow of water in the vapour phase in the arid-zone soils during the monsoon. The post-monsoon season is one of continuous decrease of heat storage with the least fluctuations (Krishnan and Kushwaha, 1974).

Over the sand-dunes, also, the soil temperatures reveal diurnal and seasonal variations similar to the pattern observed in sandy plains.

Frequency of occurrence of dust storms in western Rajasthan

The mean number of dust storms (approx. 8.7 per year) is maximum in Jalore and ranges from 5 to 6 per year in Nagaur, Churu, Ganganagar, Jodhpur and Phalodi. Most of the storms occur in May and June. A detailed analysis of the hourly visibilities and wind speeds recorded at Jodhpur during May and June of each year from 1967 to 1972 was carried out and the frequencies of occurrence of the dust haze were compiled. The dust haze is classified as thick, if the visibility is reduced to less than 1 km, moderate, if it is between 1 and 2 km, and thin, if it is between 2 and 4 km. Out of 140 dust hazes during 1967–1972, 36 were thick, 38 moderate and 66 thin.

Though May and June during these six years experienced 68 and 72 dust hazes respectively, thick and moderate dust hazes occurred more during May. There is a considerable year-to-year variation in the occurrence of dust hazes. Both dust hazes and dust storms were most numerous during 1969 and 1970, since they were the years subsequent to the severe drought years in the Jodhpur region.

This aspect would be clearer from Fig. 1, showing the frequency of dust storms and the subsequent monsoon rainfall of that year. On the average, 8.3 dust storm per year occur at Jodhpur. But this frequency varies from year to year. It may be seen from Fig. 1 that during the period 1951 to 1972, there was an increasing trend of dust storms, whereas rainfall showed a decreasing trend. This is so, because whenever the rainfall falls steeply and is very low, in the year subsequent to it there is a sharp rise in the occurrence of dust storms. This finding has a considerable significance in the mechanism of soil erosion and desertification. Drought years and below-normal rainfall conditions result in sparse vegetation which, with excessive biotic interference, deteriorates fast and causes the soil to be blown off more vigorously. This wind erosion results in the occurrence of a larger number of dust storms and dust hazes in the subsequent year, particularly in the windier months of April to June. Thus the incidence of drought years has a multiplier effect on desertification.

The area covering the arid zone of north-western India and the adjoining arid-zone regions of Pakistan, Iran, etc. is one of the dustiest places in the world. Observations indicate that the dust blows up to 20,000 to 30,000 feet. It is also postulated that the dust over this arid zone is the main cause of the mid-tropospheric divergence that occurs over the region which does not allow sufficient precipitation to occur in spite of good atmospheric humidity.

The data of monthly variations of the average daily total and diffuse radiation on a horizontal surface at Jodhpur indicate that though its total radiation is more than that at New Delhi for all the months, the increase varies from 24 to 70 cal/cm^2/day and its mean monthly diffuse radiation is either equal to, or less than, that of New Delhi for all the months. Espe-

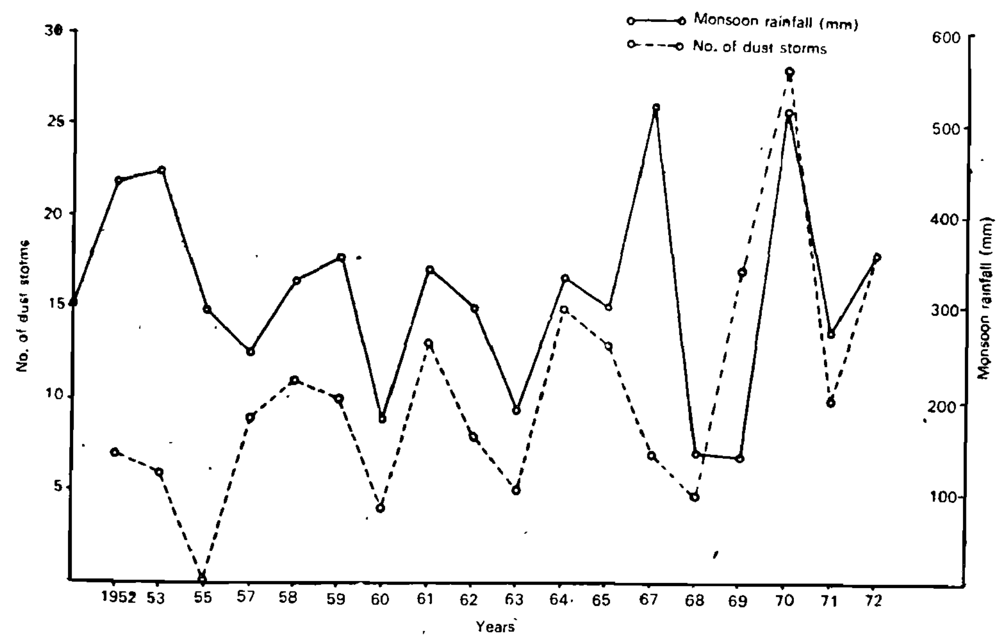

Fig. 1. Relationship between frequency of dust storms and monsoon

cially, the diffuse radiation over New Delhi is higher by as much as 46 cal/cm²/day during the hot weather period of March to June. This phenomenon may be due to the suspension of dust in the atmosphere over Jodhpur, especially in view of the fact that this effect is absent in August when the dust generally clears out after a few good rains (Garg and Krishnan, 1974).

Measurements conducted over a 3-year period (1973-1975) of dust blowing from the surface to a height of 3 metres indicate that the average amount of dust blowing on the day of a dust storm varies from 0.50 to 4.20 quintals per hectare in Jodhpur. In the case of Jaisalmer, however, where wind speeds are high, an average of 5.11 quintals per hectare is recorded. In Chandan, 50 km east of Jaisalmer, the removal of the grass cover over an area of 2,007 m² resulted in soil depletion of 1,065 cu.m within 3 years, i.e. a loss of 0.53 metres of soil depth.

The analysis of the particle-size distribution of these dust samples collected from different land-use conditions at Jodhpur indicates that the percentage of fine sand varies from 60 to 75 close to the surface and decreases with the height, being 55 to 70 per cent at a height of 3 m. The clay percentage varies from 6 to 9 in the bare cultivated soil and 7 to 15 in sites under native vegetation. Thus the higher percentage of clay in the dust particles than what is actually present in the soil of the experimental site indicates that these soil particles have been transported from distant places. There is also a very high amount of silt which varies from 14 to 29 per cent in the bare cultivated soil, 18 to 28 per cent in afforestation sites with eucalyptus-trees and 28 to 39 per cent in the sites of native vegetation. Thus there are large quantities of silt in the dust blowing at 2 to 3 metres above the ground level, thereby indicating the movement of the fertile fraction of the eroded soil to large distances. The comparatively small quantities of silt found in the dust blowing over the bare cultivated soil protected by a series of eucalyptus and other trees indicates the usefulness of wind-breaks in arresting soil erosion and fertility loss (Krishnan and Gupta, 1976).

Pattern of variation of wind speeds in the arid zone of north-western India

Very high wind speeds are recorded at almost all stations within the arid zone during the summer and monsoon seasons. The highest wind speeds are recorded in the Jaisalmer and Phalodi regions, and the next highest in the Bhuj region. The wind speeds decrease towards the north as well as towards the south from the high-wind belt of Jaisalmer and Phalodi regions. But the decrease is sharper towards the northern side than towards the southern side, as revealed by the higher values in respect of Jodhpur and Barmer than those in respect of Bikaner and Ganganagar regions. The least wind speeds are recorded during the post-monsoon season. There appear to be good possibilities of wind-power utilization in Jaisalmer, Phalodi, Jodhpur, Bhuj and Barmer regions.

CLIMATIC CHANGES AND TRENDS

Trends in the annual rainfall of the arid zone of north-western India

Banerji (1952) observed that there had been a slight decrease in rainfall during the 50 years ending in 1950 in Rajasthan, except at the stations situated in the Aravallis. But this statement has been disproved by Pramanik, Hariharan and Ghosh (1952), Pramanik and Jagannathan (1954) and Rao (1958). It has, however, been brought out by Krishnan and Ananthakrishnan (1962) that there are no secular trends in the incidence of droughts.

To study this aspect in greater detail, considering the recent data, graphs showing five-year moving averages at various stations from 1891-1975 were prepared (Figs. 2 to 4). The portion of the graph in respect of the years when the below-normal rainfall condition existed have been shaded. It may be seen that one such spell of large magnitude and duration occurred during 1962-1971 in respect of most of the stations. Actually, the decreasing trend started from 1956. Though there are 3 or 4 such spells of below-normal years, which occurred during 1901–1960, they are of very small magnitude, and the below-normal rainfall spell of the decade 1962–1971 is comparable only with a very large below-normal rainfall spell that occurred in the decade 1895-1905. However, owing to the occurrence of excessive rainfall during 1970, 1973, 1975 and 1976, the trend appears to have been reversed slightly. Thus in respect of the most of the stations, the pattern of annual rainfall is a decrease from 1956 to 1969 and an increase thereafter. The only exception to this pattern is Churu where just the reverse appears to have taken place, i.e. there has been an increasing trend during 1951 to 1963, and a decreasing trend thereafter. To a certain extent, this feature is noticeable in respect of Jhunjhunu also.

Trends in the frequency of occurrence of highly deficient rainfall weeks during the rainy season

An examination of the occurrence of large deficient-rainfall years during each decade during 1901–1970 indicates that years with large deficiencies in rainfall have started occurring more frequently since 1961 at most of the stations. This study has been carried in respect of 11 district headquarters stations of the arid zone of western Rajasthan, based on weekly rainfall data collected during 1901-1970, assuming that a week has a deficit-rainfall period, if it fails to receive at least half of its normal amount.

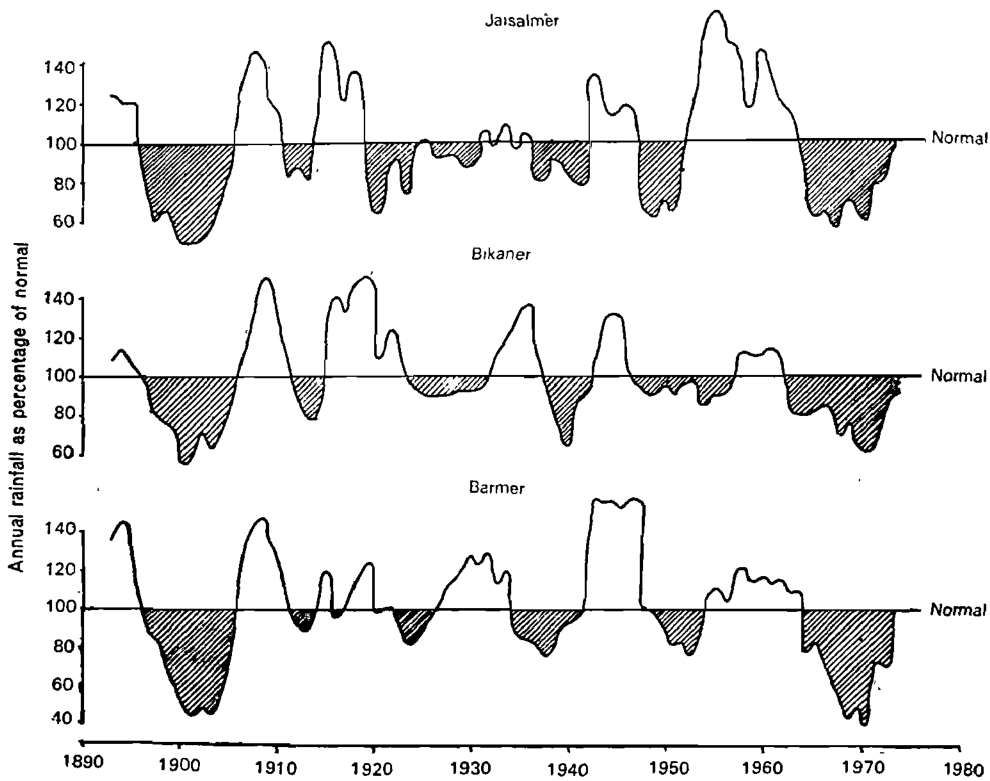

Fig. 2. Five-year moving averages of the annual rainfall of arid zone of India during 1891–1975

There does not appear to be much variation in the total number of deficient-rainfall weeks during different decades. However, there is an indication that the number of such drought weeks increased during 1961–1970 as compared with that during the earlier decade, except in the case of certain northern stations, e.g. Churu, Ganganagar and Jhunjhunu.

Aridity shifts in the arid zone of western Rajasthan

In view of the high year-to-year variability in rainfall, considerable year-to-year variations occur in the climatic pattern of western Rajasthan. Krishnan (1968b) studied the climatic classification of Rajasthan during the high-deficit rainfall year of 1941 and the surplus-rainfall year of 1944. During the former year, the arid-zone conditions prevailed in the whole State, except in the Banswara and Jhalawar regions, whereas during 1944, the arid-zone conditions were confined only to the north-western portion of the Bikaner, Phalodi and Ganganagar regions. The Barmer and Jaisalmer regions came under the category of subhumid zone. The occurrence of considerable year-to-year variation in actual evapotranspiration and moisture deficiencies in western Rajasthan during 1941-1960 has been pointed out by Krishnan and Thanvi (1969). Thus the mean aridity index in respect of all stations in various districts of western Rajasthan during different decades of the period 1901–1970 were computed, using Penman's mean potential evapotranspiration values.

Fig. 5 shows in respect of western

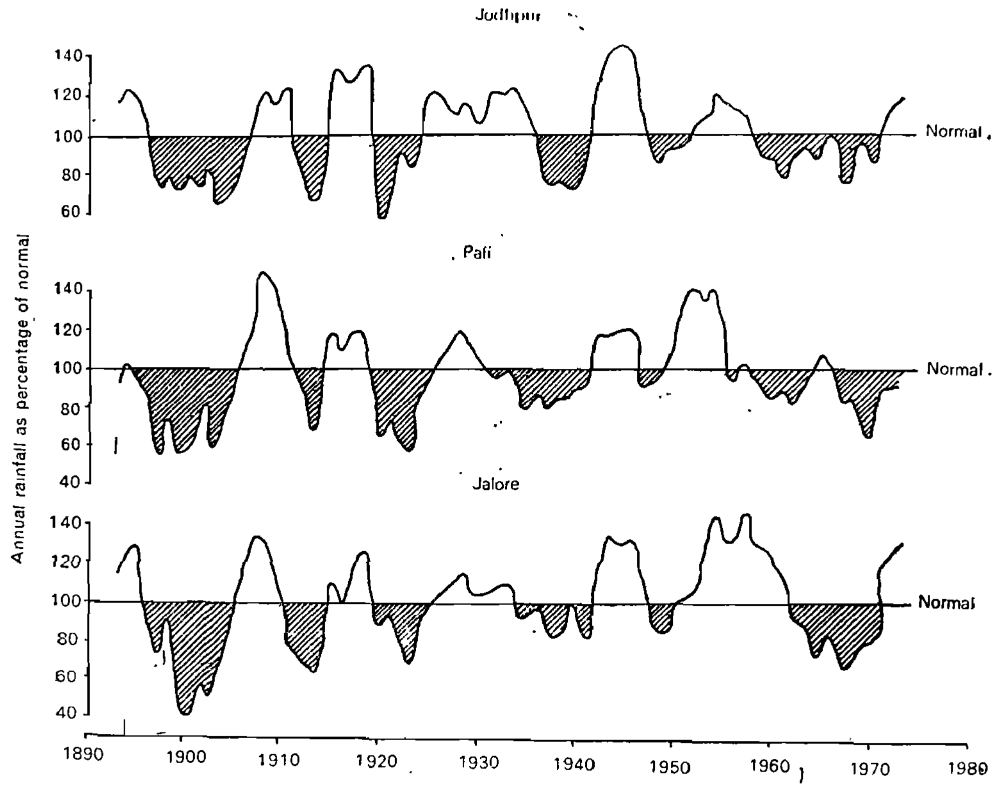

Fig. 3. Five-year moving averages of the annual rainfall of the arid zone of India during 1891–1975

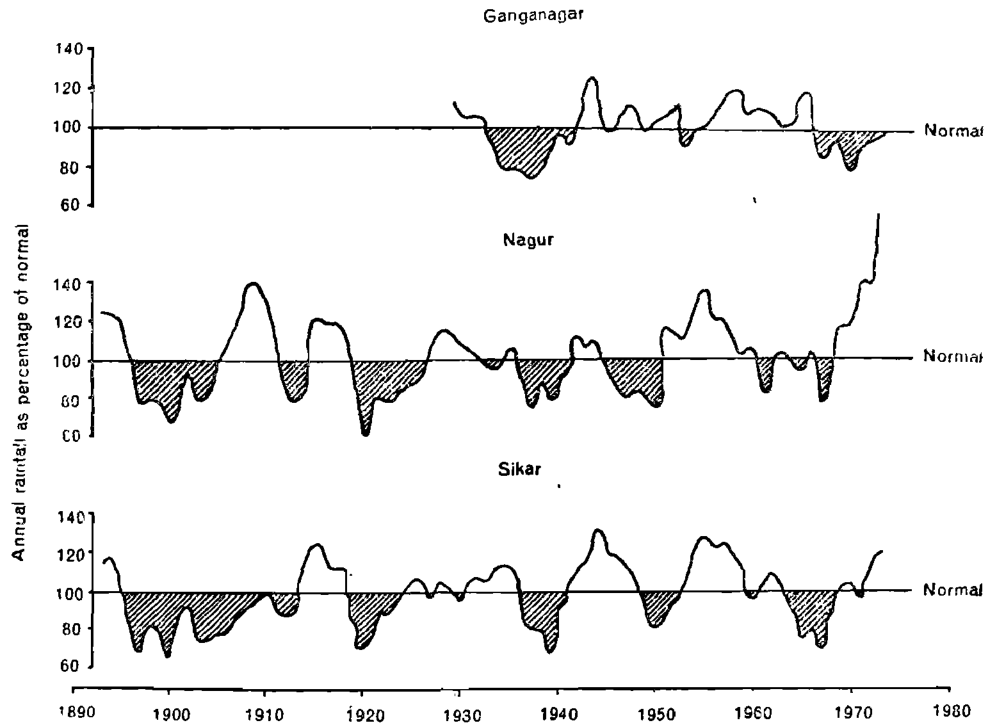

Fig. 4. Five-year moving averages of the annual rainfall of the arid zone of India during 1891-1975

Rajasthan the aridity index line of 80 for different decades of 1901 to 1970. The data in respect of all rain-gauge stations in western Rajasthan have been used for drawing isopleths.

It has been noticed that the aridity index line has shifted eastwards between the first and second decades of the twentieth century, especially in the Ganganagar, Bikaner, Churu and Jodhpur districts. This deterioration was not noticed in the Barmer and Jalore districts during that period. Thereafter, there were to-and-fro oscillations of small magnitude of this line during different decades from 1920 to 1970. However, such shifts were more marked in the north in the Churu district and in the south in the Jalore district. In the Churu district, the maximum dryness was recorded in the decade 1951-1960, when the aridity index line of 80 attained its eastern most position. However, the portion improved in 1961-1970, thereby showing that this region had been becoming very much drier since recently. In case of Jalore, the eastern shift was maximum in 1961-1970. The implication of this eastward shift of the aridity index line is that desert conditions are extending towards the east, especially in the southern region.

Trends in temperature, humidity and wind speed in the arid zone of north-western India

This analysis has been carried out in respect of a typical station of the arid zone of north-western India, viz. Jodhpur. Summer temperatures have generally been more than the normal, except during the period 1965-1971. A decreasing trend has commenced from 1960. The minimum temperatures in winter also are mostly more than the normal, based on the data of 1891–1940. There has been a slight increasing trend since 1961 onwards.

Except for minor oscillations, there is very little seasonal fluctuation in vapour pressure. However, there are considerable year-to-year variations. Interestingly, vapour pressures during 1961–1970, were below the 1940 normal values with respect to winter, from 1951 onwards with respect to summer and from 1964 onwards with respect to the monsoon.

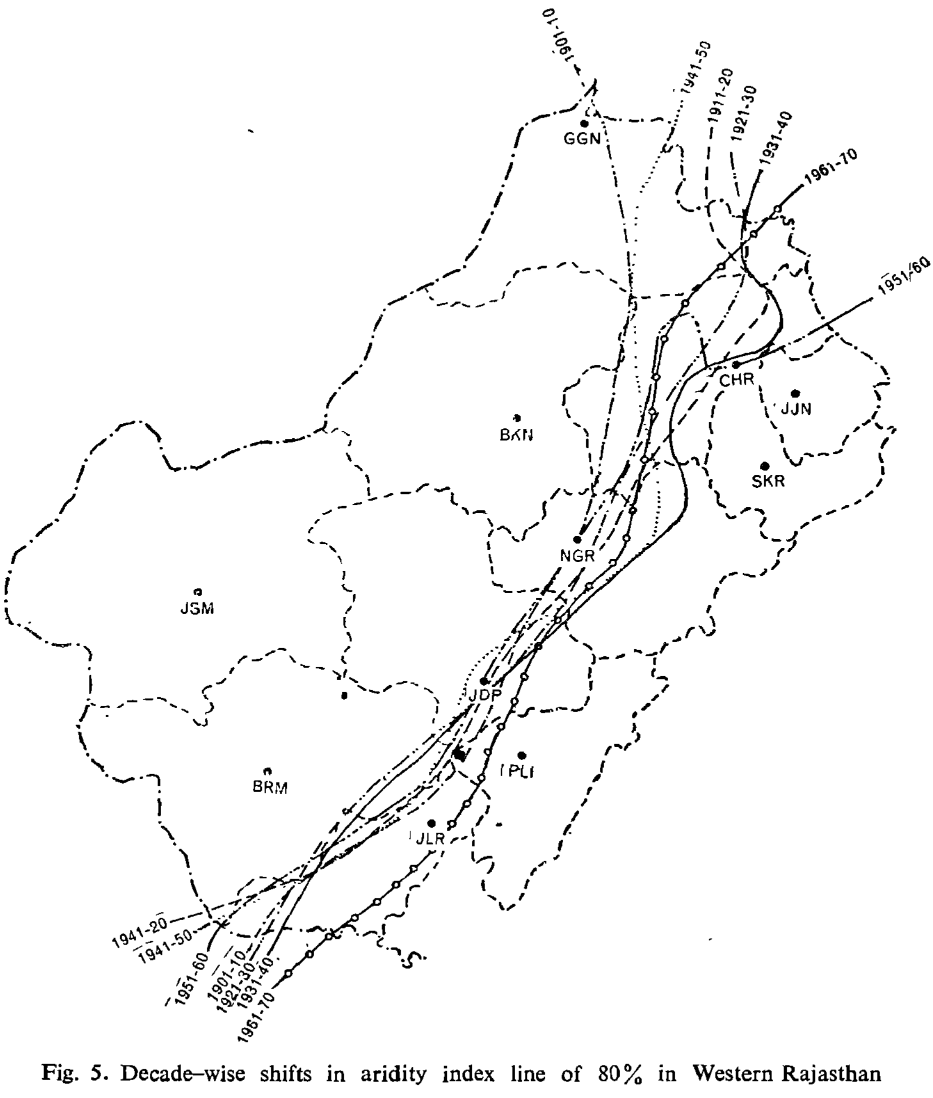

Fig. 5. Decade-wise shifts in aridity index line of 80% in Western Rajasthan

Table 4. Decade-wise surplus water available for runoff and recharge of aquifers

	1901-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970
The number of years giving surplus runoff and recharge of aquifers	2	3	4	3	4	2	3
The total amount of surplus water (mm)	376	365	341	326	555	143	81

There has been a steep fall in wind speeds during 1941 to 1947. However, the speeds gradually increased thereafter up to 1956. There is also a further gradual decline in wind speed from 1952 to 1975. Throughout the period 1941-1955, the mean wind speeds during April and September were much lower than the 1940 normals. This normal was based on the data in respect of 1897-1940.

The normal wind speed at Jodhpur for the period 1897-1940 was 15.8 km/hr, whereas speed for the period 1931-1960 was 14 km/hr and that for the period 1941-1975 was 12 km/hr, thereby clearly indicating the decreasing trend in the wind speeds at Jodhpur.

Trends in the surplus water available for the runoff and recharge of aquifers at a typical station in the north-western arid zone

A water-balance analysis for a typical station of the region, viz. Jodhpur, was completed in respect of the period 1901 to 1970, during which the precipitation was added in successive months to the soil-water storage which was, in turn, depleted through evapotranspiration losses as well as through losses due to runoff and deep drainage, subject to the upper and lower limits of the soil reservoir. The mean monthly potential evapotranspiration calculated according to Penman's method was used and the actual evapotranspiration was computed by adopting the water-budgeting procedure of Thornthwaite and Mather (1955), in which a linear relationship between the relative transpiration rate and the available soil water is assumed. From this water-budgeting analysis, an estimate of the surplus water available in the region for runoff and deep percolation and for the ultimate recharge of aquifers has been obtained. This information in respect of various decades of the period 1901-1970 is given in Table 4.

It is interesting to notice that the availability of surplus water for the runoff and recharge of aquifers was steady during 1901 to 1940 and it was maximum during the decade 1941-1950. From the decade 1951-1960, the availability began to decrease and the least value of 81 mm was recorded for the decade 1961-70. This decrease is consistent with the decreasing pattern of rainfall during the decade mentioned earlier.

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7

GEOLOGICAL HISTORY OF THE NORTH-WESTERN ARID ZONE OF INDIA

P. C. CHATTERJI

THE geological succession of the north-western arid zone of India (Table 1) is discussed in this paper.

The Pre-Cambrian Eon. This is the oldest rock-forming eon and comprises the banded gneissic complex, followed by the Aravalli system, the Delhi system and the Vindhyan system.

Banded Gneissic Complex. The banded gneissic complex is represented by meta-sedimentary rocks of two alternate bands, which are : (i) darker formations composed of mafic minerals and (ii) light-coloured formations composed of felsic minerals. The banded gneissic complex is unconformably underlain by the Aravallis in the Nagaur, Pali and Sirohi districts of western Rajasthan and continues in the Gujarat State. The formations are exposed in small isolated locations.

The Aravalli System. This system of rock formations covers the NW arid zone of India and continues right up to the NW plain of Gujarat (Palanpur region), with occasional irregular interruptions. Some isolated outcrops of these rocks are also found in the Jodhpur, Nagaur and Bikaner regions. The general strike of these formations is NE-SW. Across the Sirohi District lies a belt of fundamental schists, irregularly interrupted by instrusive tongues of the post-Delhi Erinpura and Malani granites. These schists also enter Palanpur for a short distance where they are injected with thin interfoliar veins of pegmatite which, at places, are so abundant as to form a composite gneiss. In the Sirohi region, the unsorted sedimentaries comprise slates, phyllites, mica-schists, limestones and calc-schists, with subordinate quartzites. This fundamental formation has been intruded by basic rocks of two ages, i.e. the older formations comprising epidiorites, hornblende schists, tremolite schists and amphiloilites which are older than the Erinpura granite. The younger intrusions are dolerite and belong in some cases to a period between Erinpura (*purana*) and the Malani granite (lower Vindhyan) and in other cases to the post-Malani Epoch. The lower member of the Sirohi Aravalli appears to be an anticlinally folded conglomerate which forms the bulk of the hills running north from the village Sindrat. The Sindrat conglomerate is overlain by thin beds of ferruginous shales which are further overlain by amgodoloidal basalts and tuffs, associated with which are further intermittent thin shales and quartzites. Impure argillaceous limestones are represented by calc-schists and calc-gneisses, whereas calciphyres occur among the large exposures of calcic rocks west of Kotra. In the Nagaur District, these exposures form a group of ruggedly peaked hills of quartzite. To the south-west of Gopalpura (Sujangarh), just inside the southern frontier of Bikaner, these rocks are quite disturbed, both in strike and dip, but show no signs of igneous intrusion. These beds strike parallel to the main range of the Aravallis (NW-SW). The other outcrops of these beds towards the south lie NW and SW of the Salt-lake of Didwana where the strike is NNE-SSW.

Table 1. The geological succession of north-western Indian arid zone

Eon	Era	Period	Epoch	Formation	
	Cenozoic	Quaternary	Recent	Sand and alluvium, Rann-blown sand, phyllites, etc. older alluvium and grits	
			Pleistocene	Porbander series — Calcareous and oolitic limestone.	
				Major unconformity (1) 1	
			Plio-Pleistocene	Shumar, Mar (?) formation.	
				Major unconformity (25) 13	
				Western Rajasthan	Kutch region
		Tertiary	Pliocene		Gaj series (Dwarka beds), Kankawati series
					Disconformity
			Miocene		Khari series.
			Oligocene		Lakhapat series
					Paraconformity
			Eocene	*Kapurdi. Mandal* formations. Berwali Bandah, Jogira series	Babia stage (Kirthar) Kakadistage (Laki)
				Angular Unconformity	Disconformity
			Palaeocene	Palane, Laki, Khuaila, Marh, Akali formations	Madh series
Phanerozoic				Major Unconformity (60) 120	
		Cretaceous		Barmer sandstone Abur beds, Fatehgarh Formation	Deccan Traps Bhuj series, Umia beds.
				Unconformity	
				Parihar formation	
	Mesozoic	Upper Jurassic		Unconformity	
				Bedesar formation	Katrol series
				Unconformity	
				Besakhi formation	
				Unconformity	Chari series
		Middle Jurassic		Jaisalmer formation	
		Lower Jurassic		Lathi formation, Mayakor formation	Patcham series
				Major Unconformity (170) 240	
		Permian		Badhawra formation	
				Major Unconformity (215) 35	
		Permocarboniferous		Bap Boulder Bed	
	Palaeozoic			Major Unconformity (275) 60	
				Birmania/Bilara formation/ Nagaur series	
		Early Palaeozoics		Unconformity	
				Randha formation	
				Unconformity	
		Early Palaeozoics		Jodhpur formation/Rol Quazian-Bhakari series.	
				Major Unconformity	
		Vindhyan		Vindhyan system	Vindhyan sandstone (Bhander series) Unconformity Malani series

Table 1. (Contd.)

Cryptozoic or Pre-Cambrian	Algonkian		Major Unconformity (500) 610-725	
		Proterozoic	Basic Intrusion Delhi system	(Ajabgarh series) Erinpura granite Alwar series
		M.Pre-Cambrian	Raialo series—Eparchaean interval (1000) Aravalli system	
			Unconformity	
	Archaean	L.Pre-Cambrian	Banded gneissic complex.	
			Major unconformity (1,500)	

Note : Figures without brackets show the total duration of the group or system in million years, whereas those within the brackets show lapses of time from the beginning of the particular era or period to the present.

Slates predominate, but minor amounts of quartzites and small veins of white quartz also occur in the area. Near Khatu, slates underlie the Vindhyans and a ridge of quartzite projects from the plain east of the Vindhyan scarps. Near Degana, the phyllites are associated with the wolfram-bearing granite of the Rewat Hill which intrudes into the phyllite. Similar exposures also occur at several localities near the gneissic area of Harsor (Pascoe, 1950).

Raialo Series. Resting unconformably on the softer and weathered Aravallis there are thick series of sediments forming the finest marbles in India. It is these marbles that contributed to the grandeur and beauty of the famous Tajmahal. They are about 600 m in thickness comprising limestone with basal conglomerate, sandstone and quartzite. The famous Makarana marble is of the câlcite type, possibly injected by thin veinlets of pegmatite and epidiorite. The other Raialo exposures are at Ras and Godwar, both in Marwar. The strike of Makarana marble is NNE-SSW with a steep eastern dip. Near Ras, several outliers of the Raialo series are disposed in two elongated, overfolded isoclines, striking NE-SW. This group of limestones extends for about 60 m along the strike in the form of almost continuous ridges. At Ras, the limestone bears a similar concordant but unconformable relationship to the overlying Delhi system. The enveloping gneiss is much intruded by pegmatites of the Erinpura age. They are without limestone (Adyalkar, 1964).

In Godwar area, the calcareous schists in contact with the Erinpura granite are seen to have been transformed into a similar white crystalline marble which is quarried at Saraungwa. The Raialo basin of sedimentation forms a part of the great and more extensive geosyncline, in which were later deposited the rocks of the Delhi system, and in respect of time interval belong to the Great Eparckaean interval of Indian Geology (Pascoe, 1950).

The Delhi System. With further unconformable relations are found the rocks of the Delhi system extending from Narnaul in the NE to Sirohi and Palanpur in the SW with detached outcrops at Khetri, Saladipura, Sikar and Sirohi-Godwar borders. The strike and dip of this system are the same as those of the Aravalli system. The rock formation comprises quartzite, arkose, grits, sandstone and conglomerates of the older Alwar series, followed by a set of younger rocks comprising phyllites, biotite-schists, calc-schists, gneisses limestones, etc. The rocks of the Delhi system are presumably deposited in the Aravalli geosyncline basin after the folding and erosion of the Raialos and a further deepening of the basin. The Delhis are invaded extensively by large bodies of granite and pegmatite of the Erinpura suite, resulting in the metamorphism of the Delhis and of the pre-Delhi sediments with the maximum intensity

Recent and sub-Recent (Quaternary)		Soil, blown sand, alluvium and *kankar*
Delhi System (Algonkian)	Ajabgarh Series	Slates, phyllites, mica schists, quartzitic sandstone and impure limestone
	Hornstone breccia, Kusalgarh limestone	
	Alwār Series	Quartzites, arkase, grits, conglomerates, mica schists and contemporaneous volcanic rocks

in the core and decreasing outwards (Heron, 1935).

The general succession of the Delhi system of rocks in the Mahendragarh District (Haryana), as proposed by Heron (1917), is given above.

Basic Intrusives. The amphibiotic rocks, though older than Erinpura granite, are intrusive in nature. Dolerite and basalt are younger than Erinpura granites (Pascoe, 1950).

Erinpura Granite: The Erinpura granite and its modifications are found extensively developed within the Delhi belt from Palanpur and Idar, up to Godwar and Sirohi, with interrupted exposures beyond Ras, Sikar and Narnaul. The Abu batholith is composed of the Erinpura granite suite. At Mundwara, this granite is affected by the Malani suite (of different types) of igneous rocks. At the village of Duata, this granite is intruded by the Malani suite. Waloria and Bhamoria are the other exposures of the Erinpura granite in the Sirohi District. At Chokre-Chopali, in the Sikar District, the granite contains fluorite. At Bairat, numerous veins of a fine variety of granite can be observed penetrating the epidiorite adjoining the main base (Pascoe, 1950).

Three Phases of Basic Intrusion. Three phases of basic intrusion have been described for Sirohi, of which the first occurred during the Aravalli time, the second during the Delhi and the third during the post-Erinpura age. These intrusions produced dykes, intersecting the Erinpura granites, and are regarded as pre-Malani and post-Erinpura granites in age (Pascoe, 1950).

The Vindhyan System. In the north-western arid zone after the formation of the Delhi system, the sedimentary deposition was stopped during the Lower Vindhyan time when the basic dykes and the acid igneous suite of the Malani series came into existence (Adyalkar, 1964). However, Saxena and Chatterji (1965) have reported the occurrence of the Vindhyan sandstone, sandwitched between two beds of rhyolite, the lower one porphyritic and the upper one tuffaceous. Blandford (1876) observed the basic dykes of the Lower Vindhyan age at Lawa and Pokaran.

The Malani Series. The Malani series forms a group of acid igneous rocks in the form of volcanic flows and tuffs, together with their plutonic and hypabyssal equivalents in the form of Jalore aud Siwana granites. Malani rhyolites are of acidic type and embrace felsites, depetrified lavas and glassy rhyolites intercalated with acid tuffs and pyroclastic material. The flow structure in rhyolite is very clearly and significantly seen. Pascoe (1950) has further regrouped the Malani series as under:

(a) MALANI GRANITE AND VOLCANIC SUITE. The lower boundary of the Malani rhyolite in Marwar is seen in the Miniari section only.

(b) MALANI GRANITE AND ITS HYPABYSSAL EQUIVALENTS. These minerals are found in the Sirohi, Jodhpur region and in the Hissar District (Haryana). In the Sirohi District, they are found in the Banu, Isri and Nandwar hills. In the Jodhpur region, they occur at Sarora, Jalore, Degana (Rewat Hill), and Lodsar and Taonra-Khuli (Bikaner District) and at the Tusham Hill, Khankak Hill and at Deosir in the Hissar District.

(c) MALANI VOLCANICS. The Malani volcanics are present in the Jodhpur region and in the Sirohi, Jhunjhunu, Churu, Jaisalmer and Hissar districts. In the Jodhpur region, the lavas have been traced from Pokaran to the centre of the Sirohi

District, where it is encountered at Jharoli-Ban, Panta Hill and Mirpur-Undwaria. Rhyolite also occurs in the area west of Barmer. In the Churu District, the Biramsar hill is composed of the Malani rhyolite tuffs converted into rough grey slates, which have been crushed and broken. The beds are vertical and strike NNW-SSW. Rhyolites also occur at Randisar, Lodsar and Taonra.

(d) BASIC INSTRUSIVES. The suite of the basic igneous rocks around Sankra in the Jaisalmer District is only the last phase of the basic intrusions (Bhushan, 1973). Chatterji (1966) is of the opinion that the Malani acidic suite erupted much later and had flowed over the granitic pluton as slowly creeping lavas. The basic magmas erupted at a later period when the granitic magmas had already solidified.

Sedimentaries of the Upper Vindhyan Age. At the end of the volcanic activity, there was a period of quiescence in the Late Vindhyan times, with the establishment of two (or possibly one continuous in the earlier times) arcuate sedimentation basins in which there were laid down the deposits forming the Vindhyan system of the Trans-Aravalli region. These two basins meet at a point near Jodhpur. The lower red to fawn sandstone member, with a basal conglomerate band often rests unconformably on the steeply dipping Aravalli slates. It is coarse-textured, with occasional gritty bands and with an abundance of ripple marks of varied nature. The sandstone member is succeeded upwards by limestone. To the east of Bilara, dark-grey bituminous limestone crops out. It emits fetid odour when freshly chipped and, on distillation yields a small quantity of oil and a dirty-smelling inflammable gas. From the association of the rich gypsum beds in the Nagaur area, it is inferred that the deposition of the upper Vindhyans must have taken place under continental, arid and semi-arid conditions, unlike those in the cis-Aravalli region where it is marine. From the overlying Gondwanas in the region, the deposition has been assigned an age between the Late Pre-Cambrian and the Early Palaeozoic (Adyalkar, 1964).

At two places, Sojat and Khatu, the almost horizontal Vindhyans are clearly seen lying unconformably upon the nearly vertical Aravalli slates, elsewhere the Vindhyan sediments have been laid down upon a floor of Malani volcanic rocks or upon that of the Malani granite in the north of the Jodhpur city. Sir Cyril Fox has equated the Jodhpur sandstones with those of Pokaran and both with the Vindhyan. He has remarked on the resemblance between the Pokaran sandstone and the purple sandstone of Salt Range (Pascoe, 1950).

According to Pareek (1975), these sediments, which were deposited, included the trans-Aravalli Vindhyans (Marwar-super group) traceable from Ladnu, Ratangarh, Sardarshar in the east to near Pokaran and north of Pokaran in the west and Jodhpur and Sojat in the south to as far as Hanumangarh in the north. This basin must have continued NW in the Salt Range. The trans-Aravalli Vindhyans got truncated from Merta Road to Bilara, but are widespread in the NW portion. The rock formations have been classified into the arenaceous Jodhpur group, the calcareous Bilara group and the arenaceous Nagaur group. The initial deposition of rock formations took place in the sublittoral intertidal zone. The stratigraphic sequence of the rock formations, based on lithological characters, order of superposition and strike continuity, is given below :

The Plaeozoic Era. After the end of the Pre-Cambrian Era, rock fotmation of the Early Palaeozoic Era, such as the Randha,

Nagaur group	Tunklian formation, Nagaur formation	
Bilara group	Pondlo formation, Gotan formation, Dhanappa formation	
Jodhpur group	Girbhakar formation	(Upper Garsuria formation)
	Sonia formation	(Lower Garsuria formation)

Jurassic	Jaisalmer formation, Lathi formation	
———	Unconformity	Nagaur series-Bilara limestone
Palaeozoic (?)	Birmania formation	Roll Quazian series-Jodhpur sandstone, Bhakrod series.
———	Unconformity	———
	Randha formation	
———	Unconformity	———
Pre-Cambrian		Malani, Jalore, Siwana Igneous suites.

Birmania/Bilara formations, came into existence.

The Randha and Birmania formations. Isolated outcrops of the Randha and Birmania formations occur near Virbhani in the Jaisalmer District and they are considered to be correlated with the Jodhpur and Bilara groups of the Marwar super group of the trans-Aravalli Vindhyans. The geological succession of the rock formations, as given by Muktinath (1969), and recently by Madhava Rao (1973-74), are shown above.

The structural feature of the Birmania area is considered to be a system of symmetric, doubly plunging, longitudinal sharp apex, open folds, having a general strike of NNE-SSW dipping at 35°-80°.

The Permo-Carboniferous period. After the Birmania formation, the lowering of temperature had taken place in the whole of the Godwana land during the Permo-carboniferous period and the glaciation led to the deposition of the Bap Boulders and the Pokaran Beds.

Bap boulder. In the vicinity of Bap is an irregular exposure of a boulder bed, in all probability equivalent to the Talchir, representing thereby evidences of Permo-carboniferous glaciation in the trans-Aravalli region. The Bap bed consists typically of sub-rounded to rounded pebbles, boulders and cobbles of Malanis, calcareous suite of Vindhyans and the Aravallis embedded in a matrix of marl with abundant evidences of striations. A boulder bed of smaller magnitude has also been reported to the east of Pokaran. It is over this land of Bap-Pokaran that thick sheets of ice had once accumulated, and over which descended the glaciers in their journey towards the Salt Range in the north-west (Adyalkar, 1964).

Palynological studies indicate that the bed of the Bap boulder is of the post-Miocene (Pliocene-Pleistocene) age (Lukose *et al.*, 1974). Based on field relationships and geomorphological and structural considerations, Mukhopadhyay (1971-73) regards the bed of the Bap boulder younger than the Bhadawara formation.

Bhadawara formation. This formation occurs as fossiliferous sandstone outcrops near Bap and Bhadawara. It is interpreted that the marine Bhadawara formation overlies the bed of the Bap boulder and that its age is upper Carboniferous. The outcrop is located about one km, NW of Bhadawara up to Harbans.

The Mesozoic Era. At the end of the Palaeozoic Era, the temperature increased and it caused aridity during the early Mesozoic (Triassic period). There has been no deposition in this region during this period and, as a result, a major break in the sequence of deposition took place.

The Jurassic system of Kutch. The Tethys sea of Jurassic and early Cretaceous times is considered to have extended beyond the main Himalayan axis into the region of the lesser Himalaya. It is considered to have extended into Baluchistan, the Salt Range further south through a portion of Rajasthan into the region of Kutch, and thereafter westwards as far as Madagascar. Pascoe, (1950) has given a synopsis of the Kutch Mesozoic succession as shown in the following page.

Mesozoics of Western Rajasthan. In western Rajasthan, no depositional records of Triassic period are seen. The triassic period was followed by the deposition of Lathi, Jaisalmer, Baisakhi and Bedesar formations of Jurassic times and Parihar

		Tertiary period	
		Major unconformity	
Createaceous	Deccan Traps, Bhuj series Umia series including Ukra beds		Fossils, ammonites
Mesozoic Era	Katrol series (Agrovian to Kimmordigian)	Brown and red iron stone. Basal ammonite beds Jurum Belemnite marls Kant Kot sandstones	Brachiopods, Actinozoa, Lamellibranch Cephalopoda, etc.
Jurassic Period	Chari series (Calovian to Divesian)	Dhosaoolite, Atheleta stage, Ancept stage, Rehmani stage, Golden oolite	
	Patcham series (Batnonian)		
		Major unconformity	
Pre-Cambrian Eon	Granites and metamorphic complex with intrusions of syenite		

and Abur formations of Cretaceous times. The Barmer formation has been assigned the cretaceous Eocene age (Pareek, 1975). The geological succession of Mesozoics of western Rajasthan and Kutch is shown below.

Lathi formation. On the north-western side of the boulder beds at Bap is an ill-exposed thick series of shaly sandstones and clays. This series is also seen between Pokaran and Jaisalmer. These beds with a slight dip to the W-NW occur stratigraphically between the boulder beds and the marine Jurassics of Jaisalmer comprising limestones. They are often associated with a rich assemblage of drifted silicified wood of varying sizes, which, according to Blanford, is dicotyledonous, suggesting a Triassic to lower Jurassic or even younger age. Other fossils are silicified gastropods, leaf impressions, etc.

Jaisalmer Series. This series comprises limestones inter-stratified with sandstones. The rock formation of this series overlaps the Lathis. This series is marked by a rich assemblage of bivalvafauna, ammonites, brachiopods and lamellibranchs, gastropods, corals and fossil wood.

Baisakhi formation. These formations are exposed further to the NW of the Jaisalmer series from Mohangarh to the SW of Jaisalmer. They have, of late, come to be known as "Baisakhi". Das Gupta (1975) has subdivided this formation into:

Baisakhi	—	Rupsi member
Series		Ludharwa member
		Baisakhi member

		Western Rajasthan	Kutch equivalents
		Tertiary Period	
	Cretaceous Period	Major unconformity	
		Barmer sandstone, Abur formation	(Umia beds)
		Unconformity	
		Parihar formation	(Upper Katrols)
Mesozoic Era	Jurassic Period	Unconformity Bedesar formation	(Middle Katrols)
		Unconformity	
		Baisakhi formation	(Lower Katrols)
		Unconformity	
		Jaisalmer formation	(Middle & Upper Chari)
		Lathi formation, Mayakar formation	(Lower Chari to Patcham)
		Major Unconformity	
		Palaeozoics	

Quaternary Period	Recent and Sub-Recent Pleistocene		Porbandar series
		Major unconformity	
Tertiary period		Pliocene (Mancher)	Kankaltati series
		Disconformity	
	Miocene, Oligocene		Khari series, Lakhapat series
		Paraconformity	
	Eocene Kirther Lakhi		Berwali series—Babia stage-Kakdi stage
		Disconformity	
	Paleocene		Madh series
		Major unconformity	
Mesozoics			Deccan traps

This formation contains ammonites, balemnites and some ferns.

Bedesar formation. With further unconformable relation overlapping the Baisakhis, there is a group of sandstones and grits, called Bedesar Sandstones, striking N 30°E to N40°E. The Bedesar formation has beds of golden olliles. Ammonites, virgatosphinates, densiolicatus, *V. communis,* aulacosphinates, belemnite, terebratulids, fish teeth, etc. are associated with this formation.

Parihar formation. Sandstones of the Parihar group overlie conformably the Bedesar formation. The Parihar series resembles the Umia beds of Kutch and has no fossils associated with it, although some plant remains have been found. Das Gupta (1975) has redesignated the Parihar formation as Habur formation, with a maximum thickness of 200 m.

Abur beds. This formation occurs above the Parihar series extending from the village of Sanu to Habur, and comprises sandstones, shales and fossiliferous limestones. Fossils, ammonites, belemnites and deshysites are associated with this formation.

Barmer sandstones. This formation occurs to the NE of Barmer, and has fine to medium buff sandstone and conglomerates, and contain fossils of fish teeth and plants.

Tertiary period. The Tertiary formations are found in the Kutch region and western Rajasthan.

Tertiary formations of the Kutch and Jamnagar districts. Vyas (1973) has reported that this formation forms the fringes of the entire southern rocky strip of the main land of Kutch and also borders on the Jurassics in Patcham, Khadir and Bala and the Cretaceous and Jurassics in Wagde highlands. The Nummulitic limestones and shales of Eocene are exposed and border on the traps in the south up to Lakhapat. Various types of fossils-foraminifers, lamellibranchs, echinoderms, gastropods, corals, bryozia, etc. are associated with these formations. The general trend is East to West. The geological succession is given above :

In the Jamnagar District, Tertiaries are represented by the Gaj and the Dwarka beds. The geological succession is as shown above.

Tertiary formations of western Rajasthan. The Tertiary formations in western Rajasthan comprise mainly fossil-bearing limestones and sandstones. The fossil assemblage consists of formanifers (nummulites, sp., Discocyclina, Assilina sp.), Lemallibranches, echinoids, etc. (Narayanan, 1964). The geological succession is given below:

Recent		Alluvium, wind-blown sands, limestone, kankars
	Major unconformity	
Tertiary period Middle Cretaceous to Middle Eocene		Dwaraka and Gaj beds
		Deccan traps—Basaltic lava flows
	Major unconformity- Base not observed	

Quaternary period	Recent Pleistocene	Blow sands Alluvium
	——Major unconformity Plio-Pleistocene	Shumar, Mar formation (?)
Tertiary period	——Major unconformity Eocene	Lakhi, Kirthar, Bandah Jogri formations
	——Angular unconformity Palaeocene	Lakhri, Khuiala, Mar (?) Palana formations
Mesozoics	——Major unconformity	Abur formations

Pareek (1975) has suggested geological succession for the Barmer basin as under:

Quaternary period		Recent	Blown sand, gypsite
		——Unconformity——	
Tertiary period	Upper Eocene Middle Eocene Palaeocene	Kapurdi formation Mandal formation Akali formation	Fuller's earth, sandstone with plant impressions, sandstone, lentonite
	——Major unconformity——		
Mesozoic	——Fatehgar formation Lathi formation		

Quaternary period. After the close of the Tertiary period, the entire region stood above the sea-level and was subjected to pronounced climatic episodes and weathering agencies. Owing to the physico-chemical reactions of the weathering agencies the rocks were weathered, eroded, transported and deposited. The lithological sequence during this period is divided into two major groups as shown below :

Sub-Recent formations. These formations are classified as older alluvium and are the most extensive formations of this region. These deposits are derived in part from the erosion and stream transportation of bed rock debris and in part from *in situ* weathering as sheet-wash deposits. These formations are generally cemented together by carbonates and other salts and clay, rendering them hard and compact. These salts have originated owing to physico-chemical reactions on the granite rocks of the region (Chatterji, 1968; Roy *et al.*, 1969).

Recent formations. These formations are made up of younger alluvium and blown sands which comprise unconsolidated stream-laid silt, sand and gravel and generally occur along the courses of ephemeral channels and streams. These deposits are generally medium to fine-grained and comprise largely well-rounded grains of quartz with subordinate amounts of felspar and other ferromagnesium minerals. The gravels consist of pebbles and cobbles of older rock formations of the region. Such deposits have been encountered up to a depth of over 230 m towards the Rann of Kutch. In this formation, gypsum and calcareous, silicious or ferruginous bands of varying thicknesses, from 0.5 to over 10 m, occur

	Recent (Holocene)	Blown sand and alluvium and ranns
Quaternary period	Sub-Recent Pleistocene	Older alluvium and grit Porbandar series-calcareous and oolic limestone.

three to four times at different depth horizons, thus indicating that the deposition of younger alluvium took place during occasional floods and there had been a few changes in the climatic cycles during this period (Chatterji, 1968).

Tectonic History

The Tectonic divisions of the north western Indian arid zone are given below:

Folded Belts of Pre-Cambrian Age

(1) Areas of Delhi folding

(2) Areas of Aravalli folding

Platform structures

(1) Super-order structures

(i) Vindhyan syncline

(2) *First order structures*

(i) Saurashtra-Kutch shelf

(ii) Rajasthan shelf

(3) *Second-order structures*

(i) Meri-Jaisalmer arch

Tectonic evolution. The Archaean Proterozoic folded belts, consequent upon their consolidation, formed the basement of this platform. The tectonic evolution of the platform started with the development of the several major super-order and first-order negative structures with the deposition of the Delhi sequence (Proterozoic), which represents the oldest sedimentary sequence of this platform (Narayanaswami, 1966). The Delhi sequence occupies the Delhi depression and shows in part epi-grade metamorphism and considerable faulting and thrusting. The next stage of tectonic evolution of this platform has been traced through the Vindhyan sequences, wherever they occur together, they are separated by a period of intense tectonic activity, resulting in a major change in the pre-existing structural pattern. The Vindhyan is much less disturbed, practically devoid of metamorphism with less frequent basic intrusives. This sequence has extensive development in the Rajasthan shelf. The Vindhyans represent stable shelf sediments in the lower sequence, and they change to the continental red sandstones towards the upper portion of the sequence. This platform, after the close of the Vindhyan sedimentation, experienced a positive movement and remained uplifted till the end of the middle Carboniferous. The next stage is represented by the Permo-Carboniferous glaciation evidences furnished by the Bap and Pokaran boulder beds. The next structural stage is represented by the deposition of Mesozoic sequence which marks a distinct change in the trend of further tectonic evolution of this platform. After the Mesozoics, the Tertiary formation was deposited without any disturbance and with an abundance of fossils. During the Quaternary period, the Pleistocene glacial phases occurred, though only loose sediments and alluvium were formed. In recent times, because of climatic episodes, weathering has increased and the net result is the great Thar Desert.

Palaeoclimate

The geological record in India suggests several alternations of arid and fluvial conditions in the Pre-Cambrian times. During the Carboniferous times, a glacial climate prevailed over what is now the arid zone of Indo-Pakistan. The Aravalli range at that time was occupied by an ice-sheet which extended northwards up to the Salt Range. During the Permian period, desiccation started with the advent of warm and humid climate and as a result, the Permo-Triassic period had a dry climate. This dry period was followed by a humid period and during the rest of the Mesozoic period, normal climatic conditions seem to have prevailed.

From the middle Miocene to the close of the Pliocene, the climate was humid and warm. This climate was replaced by distinctly cooler conditions in the Pleistocene. The middle and upper Pleistocene was a period of repeated glaciation (at least four major episodes have been recognized). Because of extensive glaciation over the Himalayas down to its lower altitudes, the summers in the present arid zone became cooler and evaporation became less. After the last glacial period (after Pleistocene), the western part of Rajasthan began to get gradually dry (Krishnan, 1952).

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Plate a. The strong desert winds leave gaping holes in the hardest of rocks

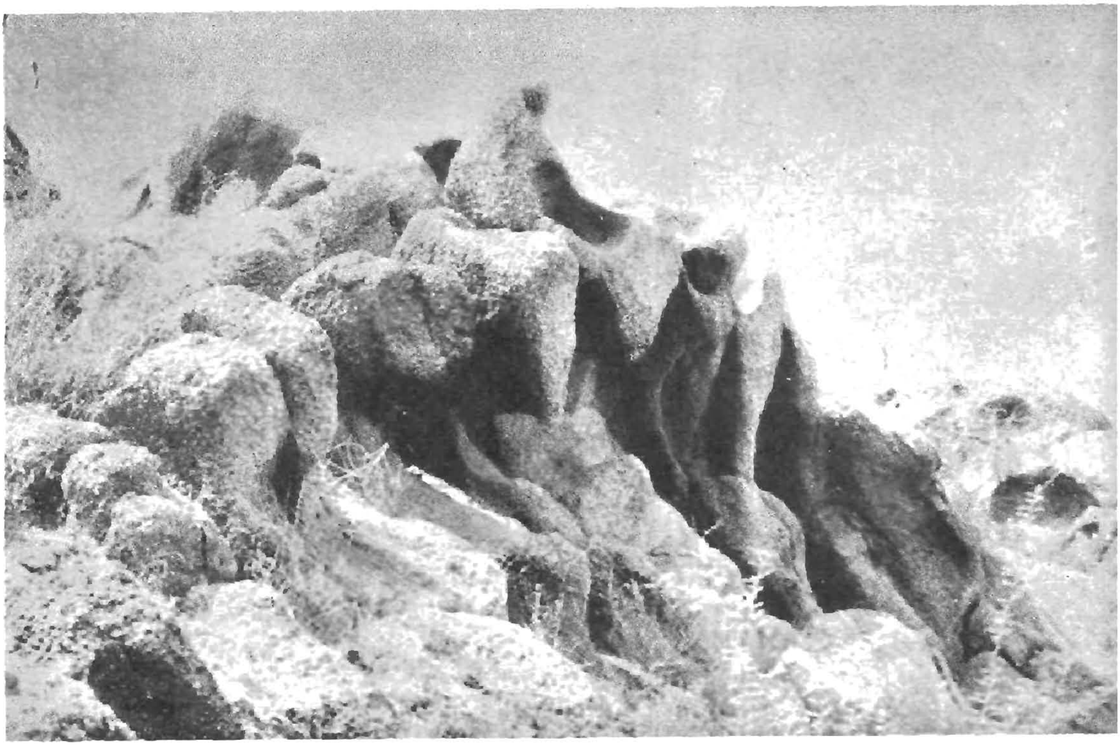

Plate b. Semi-circular tafonis developed along the joints and on individual boulders

Plate c. Rocky, gravelly pediments with gentle slope, veneer gravelly deposits and rhyolite hills in the background

GEOMORPHOLOGY OF THE RAJASTHAN DESERT

BIMAL GHOSE, S. SINGH AND AMAL KAR

STUDIES on the evolution of landforms through geomorphological processes, their geomorphological characteristics and the mapping of their distribution help to assess and evaluate the physical potential of the land for development and rational land-use planning of the desert regions. In view of the importance of the practical application of geomorphology in the environmental development and management, geomorphological investigations on the evolution, classification, distribution, analysis and mapping of the landforms by employing the photo-geomorphological and conventional research techniques, have been carried out in different parts of the Rajasthan Desert by various workers. These are summarized by Ahmed (1969), Ghose (1964), Ghose *et al.* (1977), Pandey (1968) and Singh and Ghose (1976) and the results of these investigations are integrated in this chapter.

GEOMORPHOLOGICAL EVOLUTION OF LANDFORMS

Geomorphological investigations on the evolution of the landforms of the Rajasthan Desert have revealed that they have been sculptured to the present forms by the orogenic, erosional and depositional processes. The geomorphogeny of the area is quite old and landforms from the Archaean era to the Quaternary era occur in this region. The argillaceous Aravallis of the Archaean era were laid down in a syncline existing at that time among the gneissic Archaean. After the depositional phase, the Aravallis were uplifted and put to prolonged subaerial denudation during the Algonkian era. The igneous activities which took place during this era had gone on *pari passu* with the upliftment, and these activities produced the Erinpura suite of granite along the isoclinal foldings of the Aravallis of this region. The weathering and erosion of the Aravallis continued for a long period, during which the sediments of the Raialo series, mainly limestone, and subsequently the sediments of the Delhi system, were laid down in the denudation valleys of the softer and weathered Aravallis or in the basement granites (Heron, 1917). Consequent upon the upliftment of the Aravalli range, a second cycle of erosion started when the low-lying areas of the eroded surface of the Aravallis and the exposed Erinpura granite suite were deeply weathered. Whereas the uplands were unaffected (Plate **a**). This weathered zone was later on eroded in part, exposing the underlying rocks. The exposed rocks, constituting the Algonkian surface, started being worn down by the subaerial denudation. During the Lower Vindhyan period, another igneous activity took place. The intrusives formed the Jalore and the Siwana granites and the extrusives, the Malani rhyolite. During the second crustal movement, the Upper Vindhyan formations came into being. Glaciation took place during the Carboniferous period and it was responsible for the formation of the boulder beds of Bap and Pokaran (La Touche, 1902). In the western districts of the desert, namely Jaisalmer, Barmer and Bikaner, there are evidences of marine deposits due to several marine transgressions and regressions during the Mesozoic and Tertiary eras. After the Tertiary period, this region was subjected to different climatic fluctuations, subaerial denudation and deposition. The existing major landforms of this region were formed during the Quaternary period by the fluvial and aeolian processes operating on various lithological formations and under different climatic phases. An interpretation of aerial photographs and field surveys revealed that the Aravalli drainage system, comprising the Luni River and its tributaries, and the drainage system of the Himalayan origin, constituting the Ghaggar and its tributaries, were well integrated in the past humid period and they were responsible for the formation of the vast existing alluvial plains, with varying thicknesses of alluvial sediments (Ghose, 1965). The piedmont plains and the pediments were formed as the results of slope retreat at the base of the hills of different formations. This major humid phase was followed by a major arid phase, probably in the pre-Holocene period and was terminated around 10,000 years B.P. (Singh *et al.*, 1974). During this arid phase, the high active sand-dunes, sandy undulating aggraded older alluvial and interdune plains were formed and two major drainage systems were disintegrated and disorganized. The barriers created by the formation of the sand-dunes astride the major drainage channels segmented many valleys into sandy inland basins (Ghose *et al.*, 1975). The desert extended to the east of its present limit and there was widespread desiccation.

From 10,000 to 3,800 years B.P., the climate again became humid, but it was less humid from 9,500 to 5,000 years B.P. (Singh *et al.*, 1974). The fluvial activities became intense and the high active dunes were stabilized and dissected. The sandy inland basins were filled in with water and sediments and the freshwater lakes were developed at certain places. The younger alluvial plains were formed along the rivers and their major tributaries. This major humid phase was replaced by another arid phase, probably in the late Holocene period, around 38,00 years B.P. (Singh *et al.*, 1974). Owing to renewed aeolian activities, the younger aeolian landforms, viz. barchan dunes, shrub-coppice dunes and sand ripples were formed on the old fluvial and aeolian landforms. The freshwater lakes dried up and turned into saline depressions. In the recent period, the increasing biotic activities in association with occasional severe droughts reactivated the crests of the stabilized sand-dunes, deflated and deposited the sands on fluvial and aeolian landforms, turned the fertile lands into saline lands, and intense fluvial activities dissected the old landforms.

DISTRIBUTION AND SALIENT GEOMORPHOLOGICAL CHARACTERISTICS OF LANDFORMS

The Rajasthan Desert, on the basis of its evolutionary history, form characteristics, depth, size and nature of the sediments, slope and erosional, depositional/salinity hazards, has been divided into fourteen major landform units. The distribution and salient geomorphological characteristics of these landform units are described below:

Hills. The major hilly tract of the Rajasthan Desert is the Aravalli mountain range which occurs along its eastern boundary and is composed of quartzite, schists, slate, etc. These hill ranges generally have narrow ridges, conical shape and a high relative relief. The hill slopes are generally rectilinear, with 25° to 30° angles, and their lower parts are covered with thick aeolian and colluvial sediments. All the hill slopes are dissected by numerous streams draining into the Luni and its major tributaries.

To the west of the Aravalli range, in the south-western part, there are hills composed of granites and rhyolites, flanking the range in Sirohi, Jalore, Jodhpur and Pali districts. Around Sirohi, Abu and Erinpura, the hills are composed of Erinpura granite and pegmatite and are in the form of batholiths. The hills composed of intrusive and extrusive igneous rocks of the Lower Vindhyan period are scatteredly distributed over the southern, central and western parts of the desert in the form of domes and inselbergs. The chief constituents of these hills are the Jalore and the Siwana granites or the rhyolites. All the granite hills are dome-shaped, with convex summits and concave basal slopes. The convexities of the domes have, however, been interrupted by several concavities owing to weathering and erosion along the horizontal joint planes. In many cases, the domes have also been split along the vertical joints of granite. Spheroidal weathering along the granite hills has produced boulders of different shapes and sizes and cavernous weathering has produced tafonis along the joint planes (Plate **b**).

The rhyolite, with its vertical and horizontal joints, is more resistant to weathering and is standing as rugged inselbergs and domed inselbergs. However, where the rock is more felsic than glassy, it is more susceptible to chemical weathering, producing angular and platy fragments which cover the foothills in the form of talus. Cavernous weathering features have also been observed along these hills, but the caverns are more elongated than spherical. The average slope varies from 15° to 35°.

The hills composed of horizontally bedded Vindhyan sandstone of early Palaeozoic age occur as mesas and buttes in continuous chains around Jodhpur, Deriya, Meriya, Osian, Bhopalgarh and Bilara. The hills are flat-topped, with steep escarpments of up to 90° and a debris-covered basal slope unit. The slope varies from 20° to 35°.

The hills of the Vindhyan limestone occur near Bilara, Borunda, Jeti and Barna in the Jodhpur District and around Sojat in the Pali District. These hills have rugged topography and the hill-slopes are covered with sub-angular to sub-rounded boulders of different sizes. Chemical weathering is prominent in these hills. The hills comprising the Jurassic sandstones and fossiliferous limestones, occur in the Pokaran-Jaisalmer-Ramgarh sector.

Piedmont plains. In the central Luni basin, around Jalore, Siwana, Bujawar, etc., the hills are flanked at their bases by piedmont plains (Ghose *et al.*, 1966), and are composed of thick colluvial debris derived from the adjoining hills. The total thickness of the sediments varies from 10 to 25 m in the upper part and 3 to 5 m in the lower part. In the upper part, large boulders and angular rock fragments of 2 to 3 m in diameter are dominant and the slope varies from 5° to 10°. The lower part is covered with small pebbles, gravels and gritty sand particles of 2 to 3 mm, along with silt. The slope varies from 3° to 5°. At certain places, obstacle dunes and whalebacks are formed on the colluvial sediments of the piedmont plains. All these deposits have been dissected by gullies of 5 to 25 m depth and 15 to 60 m width. The drainage patterns in this unit vary from dendritic to sub-parallel. These plains are affected by severe wind and by slight to severe water hazards.

Rocky or gravelly pediments. This unit occurs along the base of the rhyolite, sandstone and limestone hills. The rhyolite pediments occur mainly around Jodhpur, Thob, Agolai, Barmer, Bhadrajan, etc., and are characterized by gentler slopes (Plate **c**). Observations on two rhyolite pediments near Agolai (Kar *et al.*, 1976) have shown that the slope varies from 3° to 8° in the upper part, 1° to 3° in the middle part and 0°8′ to 1° in the lower part. The micro-variations in the rock characters have, however, a definite impact on the production of debris and on the maintenance of a rocky pediment. It was observed that the ideal condition of a pediment is maintained when the rhyolite is more glassy than felsic and the joints are more widely spaced. In most cases, the pediments are covered with rock fragments of various sizes and a shiny desert varnish is observed on their surface. The pediments developed on sandstone formations occur around Bhopalgarh, Osian, Chohtan, Jodhpur, Pokaran and Jaisalmer. The slope along these pediments varies from 1° to 8° and in most cases the different layers of the horizontally bedded sandstone are exposed in the form of micro-steps. The pediments, formed on limestone, lie near Deh, Rol Quazian and Pundlu and are covered with gravels owing to the easy susceptibility of limestone to chemical weathering. The slope varies from 1° to 5°. The vast gravelly pediments around Kolayat and Bap are the ideal examples of desert pavements. The surface of these pediments are covered with angular to subrounded quartz, sandstone, limestone and quartzite fragments of 10 to 50 mm in diameter. The gravels are underlain by alluvial and colluvial deposits. These rocky surfaces are not suitable for cultivation, but they can be developed into good desert catchments from which surface runoff can be harvested for drinking and irrigation.

Flat-buried pediments. This unit, flanking the rocky or gravelly pediments, is covered with 1 to 3 m deep sediments, which are mainly transported by stream channels from the adjoining hills and pedimented surfaces and are partly developed *in situ.* These sediments are underlain by hard rocky strata, but the *kankar* pan is absent. More than 50% of the sediment particles are of 0.06 to 0.12 mm in diameter. The slope of these plains is less than 1° and the drainage channels are only a few. The surface runoff that comes from the adjoining hills and rocky pediments, sinks underground and accumulates along the courses of the previous drainage channels at depth from 10 to 40 metres. This unit has good agricultural and groundwater potentials.

Sandy undulating buried pediments. These pediments occur around Ramgarh, Sri Mohangarh, Girab, Utambar and to the east of Sikar. The mode of the formation of this unit is similar to that of the flat-buried pediments, but later on these pediments have been affected by intense aeolian activities which created sand sheets of 50 to 200 cm thickness and sand-dunes of 2 to 10 m height. The slope is irregular in this unit and it varies from 1° to 3°. In the eastern part, these sandy deposits have been dissected by rills and gullies of 1 to 10 m depth and 5 to 20 m width.

Flat aggraded older alluvial plains. This unit is most extensive and occurs predominantly in the eastern part of the desert. It occurs from Ringas and Kuchaman in the north to Bali and Bhinmal in the south, and from Sojat in the east to Pachpadra in the west. To the west of this zone another wide zone runs from Bikaner in the north to Bainsra in the south The third major zone of this plain is around Ganganagar in the north-west The alluvial sediments of these plains have been deposited by well-integrated prior drainage systems which were active during the past humid phases (Ghose, 1965). Within the alluvial deposits, a thick alluviated layer of $CaCO_3$ has developed at depths of 7 to 180 cm, and in the form of nodules. This layer has been dated back to 28,000 to 30,000 years B.P., and is called as the *kankar* pan. The nature of the sediments varies from loamy sand to sandy loam and also loam, but at certain places in pockets silty clay loam to clay loam are found. The average diameter of the sediment particles is 0.06 to 0.18 mm. The slope is less than 1° in this unit and the surface-drainage channels are almost absent, except in the eastern fringe. But the courses of the prior drainage channels have good potentials of ground-water at 6–15m depth. In parts of these plains underlain by a *kankar* pan at a shallow depth, the surface runoff can be harvested and stored in tanks and reservoirs.

Saline flat aggraded older alluvial plains. This unit occurs mainly around Bijasni, Manaklav, Mori Manana, Bhetanada, Bhawi, etc., in the Jodhpur District, around Hemawas and Raghunathgarh in the Pali District around Suyali, Karmawas and Burad in the Barmer District and at certain places in the Ganganagar and Nagaur districts. The genesis of these plains is linked with the buried courses of the prior drainage channels. The construction of tanks and canals across the courses of buried channels result in surface and subsurface waterlogging. Consequently, the subsurface salts along the prior drainage channels come up to the surface through evaporation and capillary action and turn the agricultural fields saline (Ghose *et al.*, 1975). Mostly, such salinity occurs in the medium to heavy-textured flat aggraded older alluvial plains. The slope is nearly level, with less than 1° slope The diameter of the sediment particles of this unit varies from 0.06 to 0.25 mm.

Sandy undulating aggraded older alluvial plains. This unit occurs around Hanumangarh, Raisingnagar, Pilani, Jhunjhunu, etc. in the north, around Amarpura, Bidasar, Ladnu, Sanju, Phalodi, and to the east of Jodhpur in the central part and around Ahor, Bhinmal and Sanchor in the south. The mode of evolution of this unit is the same as that of the flat aggraded older alluvial plain, but later on this unit was affected by intense aeolian activities which have created moderate to severe wind depositional hazards in the form of sand sheets of 20 to 300 cm thickness, longitudinal and transverse dunes of 90 cm to 5 m height and sandy hummocks and ridges of 30 cm to 1 m height over the flat alluvial plains. As a result, the slope in this unit is irregular and it varies from 1° to 3°. Within the sandy deposits, a weakly developed layer of $CaCO_3$ has been observed in some parts of the desert. The hard layer of $CaCO_3$ within the alluvial deposits which are overlain by aeolian deposits, has been found at a depth of 400 cm or more. The diameter of the sediment particles varies from 0.6 to 0.59 mm. Surface-drainage channels are almost absent in this unit and rainwater flows subterraneously along the courses of the buried channels where ground-water has been found at 20 to 40 m depth.

Sand-dunes. Sand-dunes are the most spectacular landforms of the Rajasthan Desert and cover 58% of the total desert area. There are two major zones of sand-dunes. The westernmost zone lies in the western parts of Barmer, Jaisalmer and Bikaner districts and is covered with high dunes with much reactivation along their crests and flanks. To the east of this zone, another zone of high sand-dunes runs through the eastern parts of the Bikaner and Churu districts. Both the above zones are separated by the vast rocky tract of Jaisalmer-Pokaran-Bikaner-Bap sector, but they again meet in the north of the Bikaner District and extend into the Ganganagar District. Another zone runs in discontinuous patches from Sanchor through Saila, Phinch, Didwana and Lachmangarh and meets the above two zones in the Ratangarh-Churu area. These three zones comprise six types of sand-dunes, viz. obstacle, parabolic and coalesced parabolic, longitudinal, transverse, barchan and shrub-coppice.

The obstacle dunes have been formed by the deposition of sand against the windward or leeward slopes or both of the existing hills and are termed windward and leeward obstacle dunes. These dunes are generally 10 to 50 m in height and have been dissected by numerous gullies of 3 to 20 m in depth and 5 to 60 m in width. The parabolic and coalesced parabolic dunes are most dominant and are found almost in all parts of the tracts with dunes. The parabolic dunes are of 10 to 50 m in height. The slope along the crest of these dunes vary from 12° to 14° and that of the windward side is from 2° to 5°. The coalesced parabolic dunes are also numerous and have been formed by the fusing together of 5 to 40 uncoalesced parabolic dunes by a transverse ridge. The height generally varies from 10 to 80 m. In the case of these dunes, the slope of the crest varies from 8° to 16°. The parabolic and coalesced parabolic dunes are formed in the prevailing south-westerly wind direction and their orientation varies from N 42°E to N 48°E. The longitudinal dunes occur mainly in the western and southern parts of the Jaisalmer District, in the eastern part of the Barmer District, in the south-western part of the Jalore District, in the north of Phalodi in the Jodhpur District and in the north-east of the Nagaur District. The orientation of these dunes varies from N 40°E to N 50°E and the height varies from 10 to 80 m. The slope of the leeward side is 19° to 22°, and that of the flanks and windward side are 15° and 6° respectively. The transverse dunes are mainly concentrated in the western part of the Bikaner District and the eastern part of the Nagaur District and are scatteredly distributed in the Churu, Jhunjhunu, Jodhpur and Barmer districts. The dunes are of 5 to 40 m in height and the orientation generally varies from N 30°W to N 50°W. The slopes of the crests, flanks and windward side of these dunes are 22°, 13° and 5° respectively.

The above four types of dunes are of the old dune system (Pandey *et al.*, 1964; Vats *et al.*, 1976), because they were formed in the earlier arid climatic phases. All these dunes are stabilized and fossilized and have well-developed nodular or finger-type lime concretions of 1 to 100 mm in diameter. In general, the dunes to the east of the 300-mm isohyet have no fresh sand accumulation along their crests and flanks but the dunes to the west of that isohyet have 1- to 3-m-thick fresh-sand accumulations, and even barchans along their crests and flanks. Sand grains of 0.06 to 0.12 mm in diameter are dominant in all these dunes. In the obstacle dunes, the flanks have finer sands than the windward and leeward slopes. The dunes of this system can be developed into good grasslands by protecting them against biotic interference.

Barchan and shrub-coppice dunes, constituting the non-calcareous sands and being devoid of vegetation, are active and they belong to the dunes of the new system. The majority of the barchan dunes are formed to the west of the 250 mm isohyet, in the Barmer and Jaisalmer districts and in the western parts of Jodhpur, Jhunjhunu, Churu and Bikaner districts. The existing high dunes of the old system, the sandy aggraded older alluvial plains and the river-beds are the source of sand for these dunes. The barchan dunes are 3 to 10 m in height, and generally 5 to 10 barchans coalesce to form coalesced barchan dunes. The slopes of the crests, flanks and windward side of these dunes are 8° to 13°, 3° to 7° and 2° to 3° respectively. The sand grains of 0.18 mm in diameter are dominant. The shrub-coppice dunes are generally of 0.5 to 3 m in height and occur in the form of sand mounds, fence-line hummocks and low longitudinal and transverse ridges. The average diameter of the sand grains is 0.11mm. These dunes have good moisture at a depth of 50 cm throughout the year and they can be stabilized by adopting suitable stabilization techniques.

Flat inter-dunal plains. This unit in the tracts with dunes mostly occurs between the stabilized coalesced parabolic, longitudinal and transverse dunes in the northeast around Taranagar, Rajgarh, Nohar, etc., and in the western parts of Churu, Bikaner, Nagaur, Jodhpur and Barmer districts. The slope here is less than 1°.

The texture of the surface sediments varies from loamy sand to sandy loam and loam in pockets. The ground-water along the courses of the buried drainage channels occurs at 15 to 20 m depth. Owing to the hard *kankar* pans occurring 30 to 180 cm below the alluvial sediments, this unit provides suitable sites for collecting surface runoff in tanks and reservoirs.

Sandy undulating inter-dunal plains. This unit is more widespread than the flat inter-dunal plains. Intense aeolian activities have created undulations on the alluvial surfaces of this unit in the form of sand sheets, 100 to 400 cm thick, sandy hummocks, 1 to 3 m high, and low longitudinal and transverse dunes, 3 to 5 m in height. The slope is irregular and varies from 1° to 3°. This unit is affected by severe to very severe wind erosion.

Shallow saline depressions. The saline depressions of different shapes and sizes are distributed in the desert. They mostly occur at Sambhar, Kuchaman, Didwana, Lunkaransar, Jamsar, Bap, Thob, Pachpadra, Sanwarla and around Pokaran and Jaisalmer. Among these depressions, the saline Sambhar Lake covers the largest area. These saline depressions are the gathering-grounds of salts and evaporites

(Ghose and Singh, 1968). The generalized stratigraphy of the saline depressions is characterized by a layer of silt and clay, with an admixture of sand, overlain by a thin layer of blown sand and underlain by a layer of sand, followed by another layer of silt and clay, with *kankar* nodules (Singh and Ghose, 1976). The surface of these depressions is nearly level with less than 1° slope. The diameter of the sediment particles varies from 0.06 to 1.19 mm.

Graded river-beds. The Luni River and its major tributaries, viz. the Jojri, the Guhia, the Bandi, the Sukri, the Jawai, the Bandi (Khari) and the Sagi, have graded their courses in the long period of their evolutionary history. The longitudinal profiles of the Luni, the Jojri, the Sukri, the Jawai and the Khari have the gradients of 1: 600, 1:700, 1:600, 1:500 and 1:550 respectively (Singh *et al.*, 1971). All the above streams have wide and flat sandy beds, with sand bars of different sizes. Sediment particles of 0.59 to 1.19 mm diameter are dominant in the river-beds. The river banks are cut vertically during the heavy floods. In general, the banks are 1.5 to 5 m high, but the banks of the Luni, the Jawai, and the Sukri have been dissected laterally by even 7 to 10 m.

Younger alluvial plains. These plains, in narrow strips, have been formed along the banks of the above-mentioned major rivers and along the courses of the Gaggar, owing to occasional floods in the rivers and the consequent overbank deposition of the riverine materials. The width of the plains varies from 1,000 to 5,000 m, and it is widest along the lower and middle reaches of the Luni. The depth of the sediments varies from 10 to 20 m, and the *kankar* pan is absent. The size of the sediment particles varies from 0.06 to 1.19 mm in diameter. In some parts of these plains, especially near the banks, sandy hummocks of 50 cm to 2 m height and longitudinal and transverse dunes of 3 to 6 m height have been formed owing to the reworking of the riverine sands and their deposition along the banks by aeolian processes. Except the above parts, the plains are nearly level with less than 1° slope and sustain good cultivation. At certain places of these level plains, in the Ganganagar, Jodhpur, Pali and Jalore districts, salinity has developed because of the construction of dams across the Luni, the Mitri, the Bandi and the Jawai rivers.

SUMMARY AND CONCLUSION

The geomorphological evolutionary history of the region has revealed that the landforms of the Pre-Quaternary eras in the Rajasthan Desert have evolved through long periods of subaerial degradation and aggradation, interrupted by short periods of tectonic activities. The major existing landforms have resulted owing to the climato-morphogenetic processes operating during the Late Quaternary period on various lithological formations and under different climatic phases. The fluvial and aeolian landforms of the region are polygenic and bear the imprints of the past climates. The vast alluvial plains were formed by the well-integrated drainage systems in the Pleistocene period and they form the backbone of the region. The sand-dunes, sandy plains and inland basins were created by intense aeolian activities during the prolonged arid phase of the Pre-Holocene period. These aeolian landforms were stabilized and dissected during the prolonged humid phase of the early Holocene period. The renewed aeolian activities of the late Holocene period created active barchan and shrub-coppice sand-dunes and sand sheets on the existing landforms of the region. In the Recent period, the increasing biotic activities have also become important in sculpturing the landforms. Taking into consideration all the geomorphological factors, such as the evolutionary history of the landforms, their slopes and form characteristics, nature, size and depth of sediments and associated hazards, the Rajasthan Desert has been divided into fourteen major landform units. The distribution and geomorphological characteristics of these landform units have been analysed and mapped in their correct positions and mutual relationships. Each geomorphological nomenclature indicates the agricultural and water potentials of the region. These landform units, thus, have different production potentials and physical limitations which can be developed by suitable management techniques.

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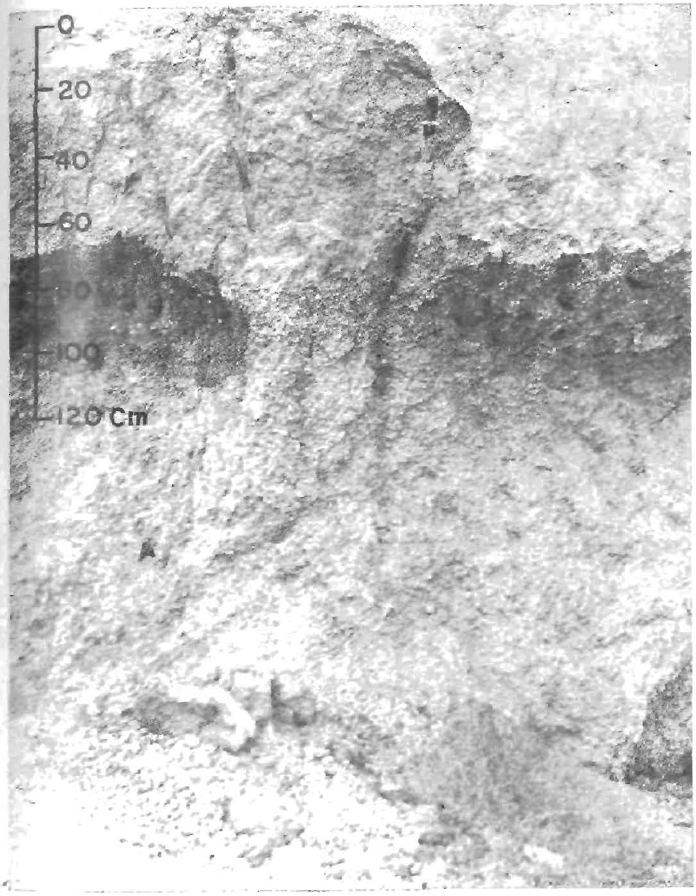

Plate d. Profile of light brown sandy soil showing range of calcium carbonate concretionary horizon

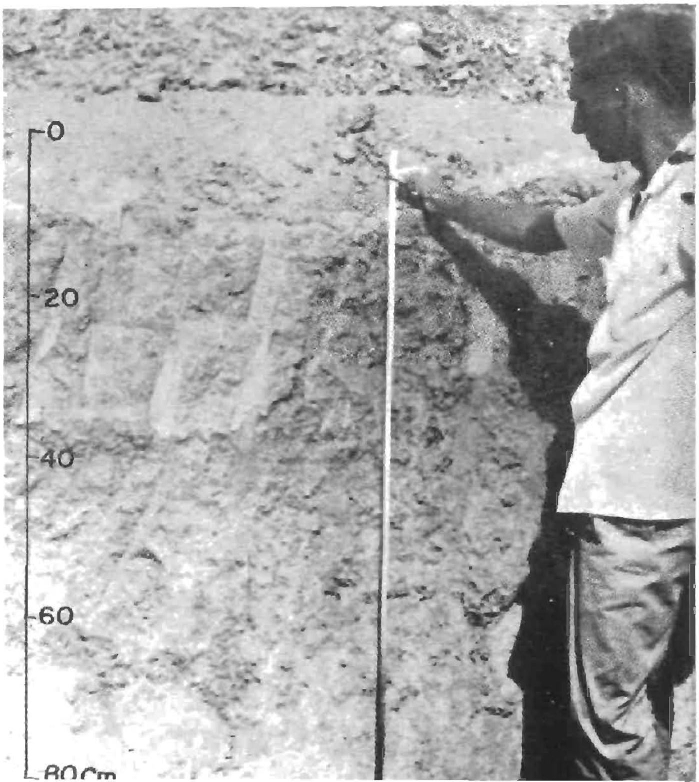

Plate e. Profile of grey brown loam

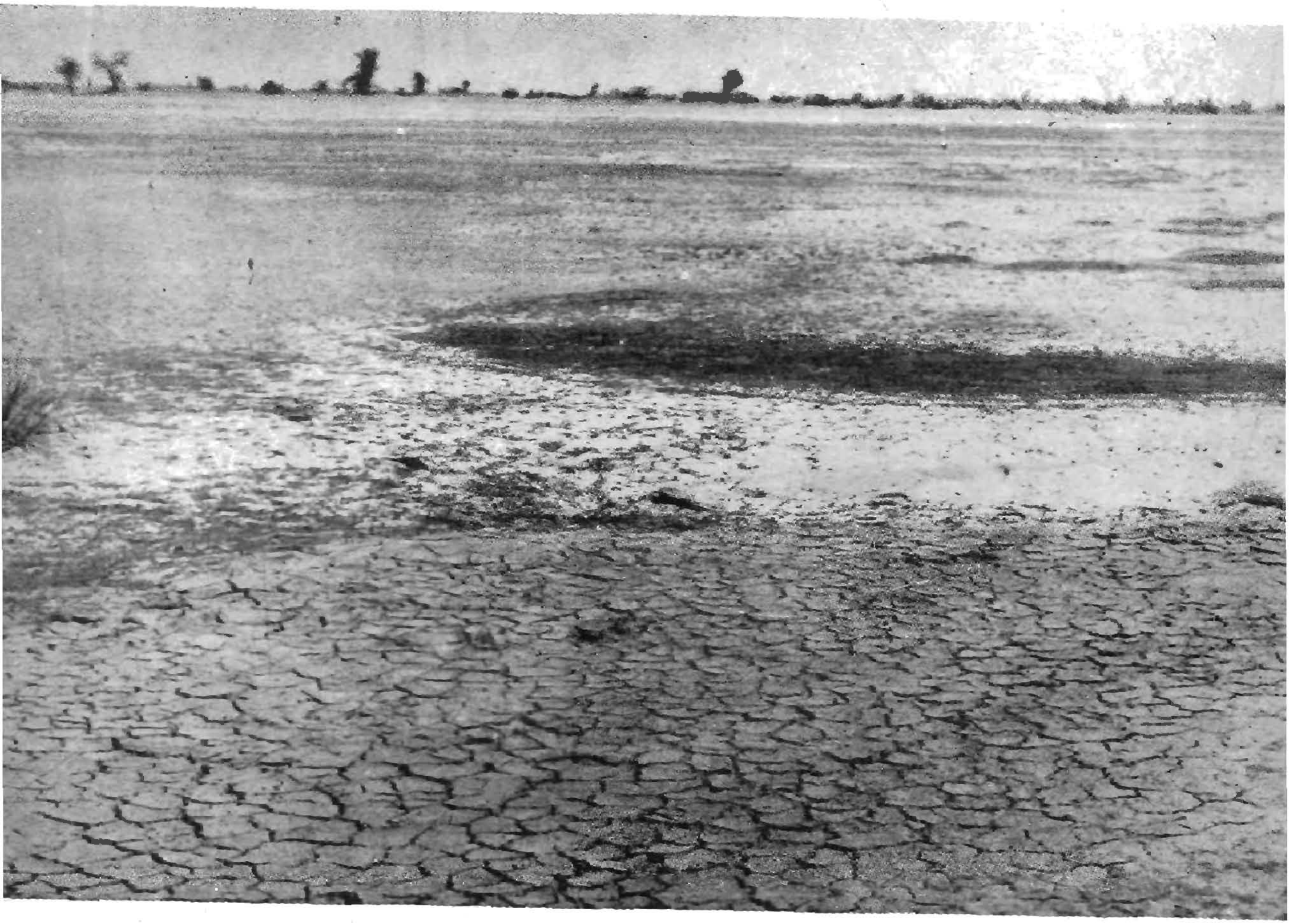

Plate f. Saline flats — a typical feature of the desert landscape

9

THE METHODOLOGY OF MAPPING LAND RESOURCES FOR RATIONAL UTILIZATION

K. A. SHANKARNARAYAN AND AMAL KUMAR SEN

THE need for accurate data and information on the physical resources of an area for scientific planning hardly needs emphasis. For this purpose, the Central Arid Zone Research Institute is conducting surveys of basic resources through a multidisciplinary team of scientists who, after classifying the lands of the areas surveyed, will prepare a composite land-resource map having the following characteristics.

a) A recurring pattern of abiotic environment, mainly landform, soil and vegetation

b) Distinct resource potentials and resource trends under any given set of conditions

c) Overall means for recommending the utilization of the resources of the area.

To realize the above obejective, the integrated land surveys had their initial start in Australia where the Division of Land Research and Regional Survey of the CSIRO has been conducting land surveys since the conclusion of the second World War. Christian and Stewart (1953) devised the 'Land system' as the composite mapping-unit which has been defined as "an area or group of areas, throughout which there is a recurring pattern of topography, soils and vegetation". This system is based on the premise that the land system is expressed on aerial photographs by a distinctive pattern and, as such, the land system can be directly mapped from aerial photographs (Christian and Stewart, 1953; Mabbutt and McAlpine, 1965). Such an approach adopted at the Central Arid Zone Research Institute, Jodhpur, since 1959, has remained bristled with difficulties in areas with immense biotic activity, such as the Thar Desert of India.

Subsequently, realizing the need to put more emphasis on soil and vegetation, along with land form and field investigations, a new concept of composite mapping was developed in Australia termed the unique mapping-area concept ('UMA'). In this system, the specialists individually draw the boundaries of soil, land form vegetation, land use, water resources, etc. on the same aerial photograph, aided by the local knowledge of the terrain. The concept was applied to the Indian arid zone by Mr McAlpine (CSIRO, Australia) and the specialists of this Institute in 1973.

Based on the land system and the 'UMA' concept and recognizing the need to account for intense biotic interference, a new composite mapping-unit termed the Major Land-Resources Units (MLRU) was developed by Abichandani and Sen (1975). This unit enables the composite mapping of areas having similar resource potential and similar management needs. In other words, besides the recurring pattern of soil, land form and vegetation, the MLRU has the recurring pattern of human activities and resource potential of an area for development-planning. The following steps are involved in the resource-mapping technique.

Base maps for integrated survey

The documentation and cartography of the base map for integrated land surveys, based on aerial photographs, was earlier, reported by Sen (1967).

The preparation of the base maps is viewed from two different ,points :

1) To provide the topographical and other informations required for the surveys
2) To provide easy means for the transfer of the survey results from the aerial photo to the base maps

Features

The following features are represented on the base map :

a) The boundary and the boundary description of the base map
b) The village boundaries with the locations of settlements
c) Physical features, such as drainage, hills and depressions
d) The auxiliary and control points for traversing and for the subsequent transfer of details to the final map
e) The aerial photo coverage
f) The co-ordinates at 5′ intervals

Documentation

The above features are of a diverse nature and are not readily available. These are collected from the following sources :

(1) One-inch (1:63,360) and half inch (1:126,720) topographical sheets produced by the Survey of India.
(2) Quarter-inch planimetric maps of the districts, showing the village boundaries, and cadastral survey maps
(3) A list of the community development blocks and the villages included in each block
(4) Aerial photographs on scales, of 1:30,000, 1:40,000 and 1:25,000 as supplied by the Surveyor-General of India
(5) Geodetic reports published by the Survey of India

The background map on which all the the information is transferred after reduction to a suitable scale at this Institute is the 1:50,000 or 1:126,720 scale maps of the areas to be surveyed.

Methods and techniques

Preparation of the initial map. The police-station boundaries and the village boundaries are transferred from the available documents to the large-scale Survey of India sheets. As the district maps and the cadastal maps ,have different scales, scale adjustments are necessary.

Aerial photographs: Orientation of the photo coverage. The available photographs are treated in the laboratory if required, to make the images more legible. The locations of important land features recorded on the initial map are then examined in relation to the photographs. Additional land features, not shown on the map but discernible on the photographs, are marked on the photogrphs for subsequent transfer to the initial map. The extent of the photo coverage of a Community Development Block is worked out by comparing the layout with the initial map, and an index map of the photographs for the block is prepared.

The coverage of each photograph is plotted on the initial map, and this coverage involves the following operations :

(1) Reduction of the photographs to the scale of the map, through an overhead projector or through a procota drawing machine
(2) To orient the photographs in relation to their positions in the map
(3) Corrections of tilt, distortions and relief deplacement in the photographs

The plotting of controls and auxiliary points for traversing and transferring details. In the proposed base map, four control points for each photograph are given. They are marked simultaneously on the photograph and the map. They are selected and plotted by adopting the stereo study and, if required, their positions are plotted on the base map by using the radial lineplotting. The exact locations, if required are verified with a plane-table survey in the field. The central points of the settlements are worked out on the photographs and subsequently transferred to the initial map with aerial photo coverage. These points can also be used as control points. While selecting the points, importance is given to the following aspects :

(1) The accessibility of the points in the field for traversing

(2) To frame triangulation on the maximum level to transfer the survey details (i.e. they should be on an average elevation)

(3) To give the maximum control for transferring the survey details through a vertical sketch master or a procota drawing-machine (i.e. they should be easily located both on the photographs and on the map)

Aerial photo interpretation for integrated survey and mapping. The aerial photo-interpretation techniques are now being employed extensively at the Central Arid Zone Research Institute for resource-mapping. The different land units can be interpreted in aerial photographs by studying the pattern and variation of the image characterstics of the objects in the photographs (Sen, 1974a, b) reflecting a similarity in land type. Hence primary importance has been attached to prepare photo maps on the basis of similar photo images. To identify the objects, the images are analysed and classified on the basis of their 'texture', 'sructure' and 'form' and their correlations (edge-gradient study). Studies on 'fishing expeditions' or on 'probability tests' are then carried out to study the photo elements. This step is followed by the study of the 'convergence of evidence' to correlate the photo elements with the existing information and documents.

Three sets of interpretations are carried out before the field survey, viz. studies on the *regional aspects, pattern elements* and *photo elements*. These studies have enabled us to prepare photo maps with similar image and the 'key' of interpretation for field checking (Sen, 1972). Once the photographic images are correlated with the type of land in the field, the sequence of events, which form a particular land unit, can often be delineated and many aspects of land, e.g. the land form, the soil, vegetation and the land-use settlement, can be inferred. After field checking, the previous interpretation is corrected, if necessary, and the final cartographic operations (Sen, 1967) are undertaken (the transferring of details, the compilation, the editing of the data, etc.).

Final mapping technique

The first order. The individual maps, e.g. those of soil, geomorphology, vegetation, geology and water resources, are prepared on these base maps by respective scientists through photo interpretation and subsequent field surveys. By faithful correlations and overlaying the units having the same landform, vegetation and soils are worked out, irrespective of their area or size. Thus a single landform or vegetation or soil may occur in units. The units, thus worked out, are likely to be more than in any individual map. Thus in the Bikaner District in the first order of mapping, 35 units are distinguished, although the number of mapping-units in individual maps is far less, being 14 in geomorphology, 12 in soils and 19 in vegetation maps.

The second order of mapping. The units, thus recognized, are further examined by the specialists to find out the possibilities to eliminate the smaller ones. If necessary, further photo interpretation or field checking are carried out. The details of the area have been limited by the mapping scale. In the mapping of 1 : 50,000 (the Jodhpur District) or 2 cm = 1 km, the MLRU with a minimum area of 0.5 sq. km or a minimum width of 0.25 km or a minimum width of 1 km can be mapped. If the mapping is done without the help of aerial photographs, the details to be cartographed will be much less. Here on 1 : 253,440 mapping, a minimum area of 4 sq. km or the minimum width of 2 km can be mapped. In the Bikaner District mapping 8 sq. km and 4 km were the minimum aimed at. Accordingly, the first-order map is revised and only 12 units are delineated. Such units are characterized by the recurring patterns of landform, soil and vegetation and can be termed as biophysica units.

The third order of mapping : To assess the resource potential of the units, the land use, the water resources, the climate, the socio-economic conditions and the existing plans, if any, for the development of the units are then examined in each unit. Accordingly, the biophysical boundaries earlier delineated are revised according to the necessity to frame the units on the basis of the homogeneity of the human factors and the planning of resources as wall. Such an exercise reduces the number of units and at the same time simplifies the map. In this way, the twelve units earlier delineated in the Bikaner District are further reduced to ten composite mapping units. Such units are the expression of homogeneous land resources according to a certain scale. As such, the units are termed 'major land resources' or MLRU.

Using the above technique, the resource survey of the Jodhpur and Bikaner districts have been completed. In the Bikaner District, ten major land-resources units were recognized (Abichandani *et al.*, 1975).

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10

THE EXTENT, RESOURCES AND PROSPECTS OF THE COASTAL DESERT OF NORTH-WESTERN INDIA

AMAL KUMAR SEN AND K. A. SHANKARNARAYAN

THE normal features of tropical and subtropical deserts—hot summers, large annual and diurnal temperature ranges, low humidity and a small amount of cloudiness—are modified to a considerable extent along the littorals owing to oceanic influences. Such areas are known as hot coastal deserts. Here, high humidity is associated with high temperature owing to direct evaporation from sea-water.

The Indian coastal desert is concentrated along the gulf of Kutch and extends into the interior of Gujarat and into a small portion of Rajasthan. The oceanic influence is extended in the north up to the head of the Luni delta. Geographically, it is concentrated mostly around the Rann of Kutch. The annual precipitation of the region is below 500 mm and the coefficient of variability of the annual rainfall (based on the data of 1901–50 rainfall) is above 60% and it means that the degree of rainfall reliability here is exceptionally low. The coefficient of rainfall variability (based on the 1901–50 data) and rainfall, temperature and humidity characteristics (standard normals based on the data from 1931 to 1960) of this area are presented in Table 1.

The Indian coastal desert conforms to Meigs' (1973) hot subtropical type so far as the climatic aspects are concerned. But from the locational point of view, it belongs to the Tropical Belt. Meigs' map (1973) includes this area within his "Kathiawar Makran Coastal Deserts" of Iran, India and Pakistan. But his delimitation of coastal deserts in India and Pakistan cannot be universally accepted, particularly the northern limit of the boundary up to Sukkar in Pakistan and Barmer, Tilwara and Jalore in India. Considering the aridity indices, drought factors, littoral locations and associated oceanic influences, the coastal desert of India extends approximately from 22°N to 25°0′ N and 68°E to 73°0′ E. From the administrative point of view, the Indian

Table 1. Rainfall, temperature and humidity conditions in the Indian coastal desert

Station	Normal annual rainfall in mm	Coefficient of rainfall variability in %	Mean monthly temperature (°C)		Average relative humidity %			
			Warmest month	Coldest month	0830 hrs	1730 hrs	0830 hrs	1730 hrs
Bhuj (Arid)	322	62·29	32·1	18·1	66	33	45	24
Jamnagar (Arid)	471	88·38	31·5	18·5	70	54	60	37
Rajkot (Semi-arid)	589	38·08	32·6	19·4	72	27	51	22

coastal desert comprises a part of the Sanchore Tahsil of the Jalore District (the Luni delta) which includes 13 villages and the southern tip of the Chohtan Block (14 villages) of the Barmer District in Rajasthan, Bhuj (Kutch), Jamnagar, parts of Rajkot (Maliya Tahsil) and the Banaskantha or Palanpur (Santalpur or Varh, Tharad and Vav Tahsil) districts in Gujarat. The total area of this coastal desert is about 65,520.8 km². This coastal desert includes the Rann of Kutch which covers about 9,000 km².

PHYSICAL RESOURCES

The coastal desert, although enclosed by sand-dunes and sandy hummocks, is not an extensive sandy area. The Kutch District, which forms part of the Gujarat peninsula is a saline tract, with stray hills. Salt marshes sandy undulating plains, sand-dunes and gravelly areas characterize the topography of the coastal deserts. The narrow strip along the Gulf of Cambay in the Jamnagar and Kutch districts have an average height of less than 25 metres. The plains of Rajkot or Banaskantha range between 25 and 75 metres in height. The rivers draining into the Rann of Kutch for the Gulf of Cambay are all consequent streams having their own local base levels. The Luni, the Rakhari, the Bhukhi, the Banas, the Saraswati, the Bambhan, the Nachhu and the Demi are the important rivers of this tract. The relative relief varies from 0 (in the coastal area) to 150 metres (in the central part of the Kutch peninsula). The coastal desert of Gujarat is underlain by a variety of rocks. The area of the Rann of Kutch practically the whole of the Kutch District and the north-western strip of the Jamnagar District is a vast expanse of tidal mud flats flanked by saline efflorescences.

In the Barmer Section (Chohtan-Bhakasar area), the northern part of the Rann of Kutch extends for about 3 km in width and 25 km in length. Its remnants representing a saline depression are evident up to Bhakasar in the north. The surface is an expanse of mud flats studded with sand-dunes, of 1 to 2 metres height.

The Luni delta. In the Jalore or Sanchore section the influence of the coastal desert extends up to the head of the Luni Delta. The Luni has a well-defined delta although no fresh delta-formation has been occurring any longer. The delta section starts fom, Chitalwana. The Luni Delta consists of a flood plain from Chitalwana to Rathora, a distance of about 6.5 km, and a delta plain from Rathora to the Rann of Kutch, about 44.8 km in length. In the deltaic plain, 'topset beds' are covered with sand and sediments for about 16 km. In the vicinity of the Rann, there are "grassland beds". In the "bottom-set beds" there are grasslands, along with silted-up deposits. The following additional characteristics have been identified: (1) the Luni has almost no water left when it reaches the delta and much of the load is deposited near the apex. Its frontal growth is, therefore, slow; (ii) the sediments being finer, the distributaries of the river tend to develop meandering courses; (iii) the supply of water to the delta has not kept itself up with the deposition, with the result that some of the distributaries have lost their heads within the present delta.

Degree and extent of sand-dunes. About 12,486 km² or 19.41% of the coastal desert in Gujarat is affected by sand-dunes. As much as 12.57 per cent (8,288 sq. km) of the area is slightly dune-infested. The sand-dunes are mostly concentrated along the coast and are of low height. About 4,558 sq. km or 6.85% of the total area is moderately dune-fed where 20 to 40 per cent of the area is affected by sand-dunes. About 18 km², of the area of the coastal desert of Rajasthan is slightly dune-fed (0 to 20% of the area being affected). The Chohtan section is strongly affected by sand-dunes (40 to 60% of the area is affected), whereas the dunes affect 20 to 40% of the land area (moderately affected) in the Sanchore Section in Rajasthan.

Ecosystem, vegetation and grasslands. The littoral type of forest is found in the creaks of the coastline in Kutch and Jamnagar. The Rajasthan counterpart is devoid of any forest. There are no reserved forests in this desert. Based on the ecosystem considerations (Fig.) of the tract the vegetation has been grouped by Rao and Aggrawal (1964) under two heads, viz. (a) strand and (b) salt-marsh.

The strand communities are again studied under two subheads: (a) sandy strand, and (b) rocky sandy strand. The sandy-strand communities are composed of either halophytes or psammophytes. Since the habitat is more or less uniform, over vast distances, the same species with a wide range of distribution can be seen almost everywhere on tropical beaches. *Ipomoea pescaprae* forms the dominant community on the sandy shores. Rao and Aggrawal (1964) have identified nine community types under the sandy-strand ecosystem. These are: (1) *Hydrophylax maritima*, (2) *Ipomoea pescaprae*, (3) *Asparagas plumosus*, (4) *Halopyrum mucronatum*, (5) *Cyperus conglomeratus*, (6) *Cyperus aristatus*, (7) *Sporobolus termulus*, (8) *Leptadenia pyrotechnica* and (9) *Cynodon dactylon*. The first two are found all along the coast and the second one is an excellent sand-binder. The third type, if found on the sandy bars, is often grazed. In the coastal area, the fourth type is a conspicuous component of the strand flora. The fifth, sixth and seventh communities exhibit dense patches on dry sandy spots and are found associated more or less with all types of strand vegetation. The eighth community type is found growing in abundance on the sand-dunes. The last community, a ubiquitous grass, is found throughout the coast, adjoining the strand vegetation.

The sandy-strand habitat is composed of water-laid loose sands which have given rise to sand-hills or sand-dunes.

The rocky-sandy strand habitat in the

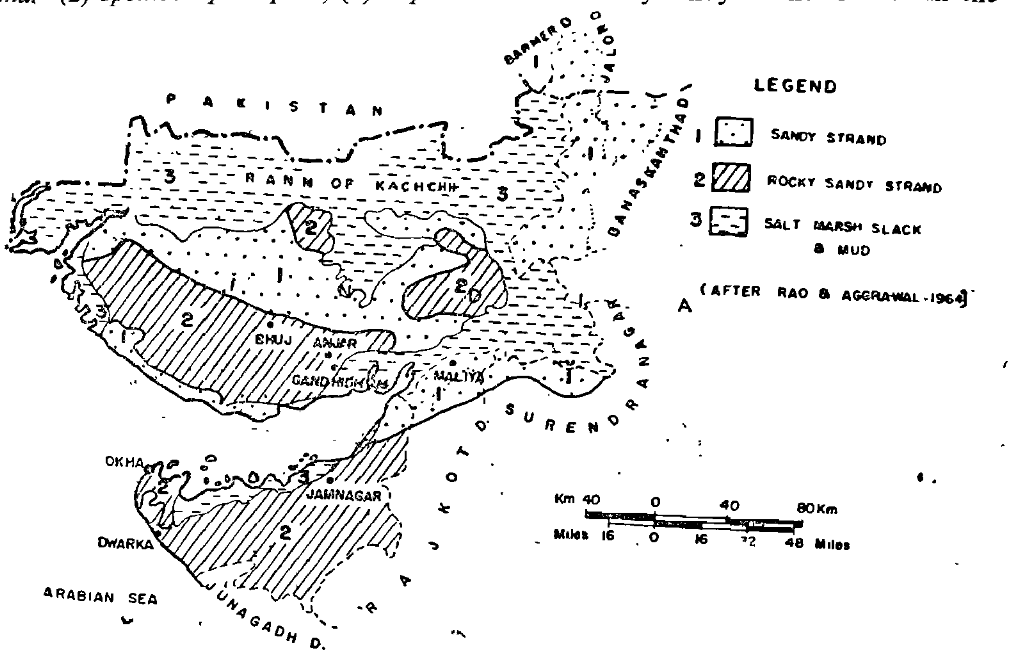

Fig. Ecosystem of the coastal desert of N. W. India coastal desert is characterized either by the presence of sand in the rock crevices or by the presence of a thin mantle of soil over the underlying rocks. This ecosystem is marked by the following predominant plant communities: (1) *Capparis cartilaginea*, (2) *Fagonia cretica*, (3) *Indigofera cordifolia*, (4) *Kickxia ramosissima*, (5) *Lepidagathis trinervis*, (6) *Sericostoma pauciflorum*, and (7) *Enicostema verticullatum* mixed species.

The salt-marsh vegetation occurs in the littoral sub-littoral belt and in the Luni Delta. The flora comprises mainly the following species : (1) *Avicennia alba*, (2) *Suaeda nudiflora*, (3) *Aeluropus lagopoides*, (4) *Fimbristylis cymosa*, (5) *Scirpus maritimus*, (6) *Urochondra setulosa* and (7) *Atriplex stocksii*. The first one is met all along the fringes of the inland creeks and shallow muddy areas. The second one is the characteristic feature of saline areas. Others are found in the interior areas.

Behind the strand habitat, salt-marshes, slacks and mud formations there lies the semi-arid coastal plain.

In short, the dominant floristic species of the Indian coastal desert are: *Capparis decidua*, *Zizyphus jujuba*, *Prosopis cineraria*, *Avicennia officinalis* and *Rhizophora mucronata*.

Geology. The Indian coastal desert has the following geological formations:

1 Recent and Subrecent: Alluvium, blown sand, milolites, tidal flats, raised beaches
2 Tertiary : (i) Pliocene — Dewarka beds
   (ii) Miocene—Gaj beds

The Deccan trap encompasses the Kutch area to a little extent. The saline marshes predominate in the Rann of Kutch and its adjoining areas. The major portion of the coastal sands is of marine origin composed of shells of marine microfauna and is very rich in $CaCO_3$.

Soils

Soils of the Indian coastal desert have been described by Rao and Aggrawal (1964) as follows:

(i) *Soils of sandy strand.* These soils are sandy to loamy-sand desert soils. Their pH exhibits moderate alkalinity. Organic matter ranges between 0.02 and 0.64 per cent. The values of total dissolved solids and sodium chloride point to the effect of salt-spray, but not to the direct inundation with sea-water.

(ii) *Soils of the rocky-sandy strand.* The soil cover over the underlying rocks has been formed by the weathering of rocks *in situ*. The soil is mixed with conglomerates. In some places, water-laid or wind-blown sands are present in thin layers over the underlying rock, and hence become mixed with the soil from the weathering rock. The soil is loamy sand. The pH shows mild to moderate alkalinity. Organic matter ranges from 0.22 to 0.81 %. The contents of the total dissolved solids and sodium chloride indicate the effects of salt spray only. Soils are highly calcareous.

(iii) *Soils of the salt-marsh.* Soils are saline and those from salt pans are sandy loam, loam or silt loam with a mild degree of alkalinity. Organic matter is much higher. Dissolved solids and sodium chloride are very high as the result of the direct influence of sea-water.

(iv) *Soils of slack and mud formations.* These soils are loamy sand to sandy loam to sandy clay loam with mild to moderate alkalinity. Organic matter of the surface soils varies within wide limits (0.26 to 4.69 %), depending upon the age of these slacks and mud formations. The content of dissolved solids and sodium chloride suggests that the soils are not under the direct influence of sea-water. All the soils are highly calcareous (40.97 to 56.58 per cent $CaCO_3$).

Ground-water resources. The geology and water-bearing formations of the area have been earlier reviewed by Adyalkar (1964). In Kutch, rocks of Patcham and Chari series comprise calcareous shales and limestone and the quality of water is, therefore, saline. The Umia series were deposited only under fluviatile and estuarine conditions and partly under marine condition. The marine formation of the series yields only saline water and hence, there is no development of ground-water in the fossiliferous sediments of the series. In the Bhuj sandstone, ground-water occurs under both confined and unconfined conditions. The static water level in the dug well ranges from 2 to 30. 5 m b.g. 1. and that in the dug-cum-bore-wells and tube-wells tapping-confined aquifers from 3.4 to 31.4 m b.g 1. Over 9,000 and 26,000 million litres of ground-water have been utilized for the purpose of irrigation in the lower and upper Bhuj series respectively in Kutch. The tube-wells located well within the Bhuj sand-stones yield about 13. 55 lps. The quality of water is generally good. In the Deccan trap in Kutch, ground-water occurs along the joints, fractures and secondary partings, which are generally limited in depth up to 50 m. The static water level in the dugwells ranges from 4 to 12 m, with yield capacities of 0.05 to 0.20 lps. The yield capacities of the Tertiaries in Kutch ranges from 0.06 to 0.24 lps, with slight to moderate saline water. Irrigation with ground-water is the universal local practice.

HUMAN RESOURCES

Data on the distribution and density of population in the Indian coastal desert are presented in Table 2. It is evident that the density is very low (below 35 persons per sq. km on an average). The intercensal decadal variation (1961–71)

Table 2. Distribution and density of population (1971)

State	District	Section	Area in (km^2)	Total population	Density (km^2)
Gujarat	Bhuj (Kutch)		45,612·3	849,557	19
	Jamnagar		14,125·1	11,11,376	79
	Rajkot/Maliya	Tahsil	657·9	58,771	89
	Benaskenta	*Varh (Santalpur)*	*1,356·1*	*55,652*	*41*
	of	Tharad	1,356 1	1,09,058	80
	Palanpur	Vav	1,651·2	97,262	59
Rajasthan	Barmer	Chohtan Bhakasar Section (14 villages)	289·4	8,701	30
	Jalore	Sanchore (13 villages)	472·7	9,140	19
	Total		65,520·8	22,99,517	35

Table 3. Rural-urban occupational structure (1971)

Industrial categories	Percentage of total working population			
	Rural %		Urban %	
	Male	Female	Male	Female
1. Primary activities (cultivation agricultural—labour, mining, quarrying)	43	31	5	4
2. Secondary activities (household industries, manufacturing other than household and construction)	10	3	23	4
3. Tertiary activities (trade and commerce, transport, storage and communications and other services)	10	3	58	6

is about 30 % being lowest in the Kutch District (21.99 %).

Workers constitute about 40% of the total population of the coastal arid zone and have a male: female ratio of 28:12. In the rural areas, about 45% of the people are workers (male: female ratio of 29 : 16). The rural and urban occupational structure (average) as a whole is given in Table 3

There is only one city, viz. Jamnagar, which has a population exceeding 1,00,000 (2,14,816 in 1971). Bhuj in the Kutch District is the next important city which had a population of 52,861 during 1971. About 30 per cent of the total population is urban. The increase in urban population during the last decade (1961–71) is of the order of 50 to 60 per cent. There are one class-I, one class-II, 4 class-III, 12 class-IV, 7 class-V and 6 class-VI towns, all located in the Gujarat sector.

RESOURCE UTILIZATION AND ECONOMIC ASPECTS

Land use. In Bhuj in the Kutch District, only 36% of the total area is cultivated. Of it, 53% is regularly cultivated, 24 % of it constitutes current fallows and 23% of it is long fallow, cultivated in 2 to 5 years rotation. About 4% of the total non-agricultural land is under permanent pastures, 6% under forests and 3% under settlements and water features. The remaining 87% of the non-agricultural area is barren and culturable waste. The Rann of Kutch is extensively exploited for salt. In the Jamnagar District of Gujarat, about 66 per cent of the land is arable and comprises net sown, short-fallow and long fallow areas. The land use pattern of non-agricultural land (34% of the total area) in Jamnagar is as follows: barren and culturable wastes—53 per cent, forests 7 %, settlements and water features 16 % and permanent pastures 24%. The land-use systems followed in other sectors of the coastal desert are more or less similar to those of the Jamnagar District. Taking the coastal desert as a whole about 55 to 60 per cent of the total area is cultivated (including short and long fallows) and about 60 to 80% of the land is available for grazing. The agricultural land when not under cultivation, is also available for grazing. The intensity of cropping is very low (100.1 to 102.3).

Agriculture. *Bajra*, *jowar* and maize are the major cereals produced. Wheat is cultivated under irrigation. *Bajra* represents more than 80 per cent of the total cropped area. Pulses, e.g. gram and peas, are generally grown in winter as a second crop after millets, and some of the pulses, e.g. *tur*, *mung*, *moth*, are grown mixed with *bajra* in the *kharif* season. The largest area under pulses is in the Kutch District. Among oilseeds, the cultivation of groundnut is gaining importance. Commercial crops are of no importance. Cotton and sugarcane are grown to some extent. The yields of different crops are, however, very low. The yields in lb per acre of *bajra*, *jowar*, wheat, barley and maize are approximately 160, 155, 900, 780 and 530 respectively (Trivedi, 1966).

On an average, less than 5% of the net sown area is irrigated. It varies from 2% in Kutch to 4 to 8 % in Jamnagar, Chohtan and Jalore sectors. Wells are the main source of irrigation, commanding 60, 96 and 99% of the total irrigated area in Kutch, Jamnagar and in other parts of the Gujarat coastal desert, and Rajasthan sector respectively. Canals irrigate about 20% of the total irrigated area in Kutch and 5% in the Jamnagar district of Gujarat.

The gross value of the agricultural output per acre of the cropped area is very low (Trivedi, 1966). The agricultural holding per cultivating household is above 17 acres in Gujarat and 21 acres in Rajasthan; the agricultural holding per head in the rural areas varies from 2 to 3 acres in Gujarat and from 4 to 6 acres in the Rajasthan coastal desert (Trivedi, 1966; Gupta, 1969). The percentage ratio between the supply per head and the requirement per head of the staple food crops varies between 117 and 175 in Rajasthan (Gupta, 1969) and from 50 to

60 in Gujarat (Trivedi, 1966) and the coastal desert.

Minerals. The coastal desert of Rajasthan has practically no minerals, although salts are often extracted from saline depressions. However, mining is not economical in this sector. The Gujarat sector is richer. Salt is extracted at Jokhan, Padana, Kandla and Mundra in the Kutch District, Jamnagar, Sikka, Salaya, Mithapup in the Jamnagar District and Maliya in the Rajkot District. Bauxite is mined in Mahadevia, Nandana, Bhatia, Gandhvi, Lamba, Bankodi, Kenedi, Ran and Virpur. Calcite is mined in Govana, Lakhasar and Narmand; limestone in Bavdial and Motigapall in the Jamnagar District. There has been an upward trend in the production of these minerals recently (Trivedi, 1966). There are extensive areas underlain by strata hopefully containing petroleum and natural gas.

Industries. The Indian coastal desert has not yet been industrially developed, unlike similar tracts in western Asia and in the Southern Hemisphere. Gandhidham in Kutch and Okha and Jamnagar in the Jamnagar District are the most important industrial centres.

PROSPECTS FOR DEVELOPMENT

Considering the limitation of resources and the constraints imposed by the arid environment, the Indian coastal deserts have restricted choices for development. The resources of the region have not yet been fully assessed. For this assessment, integrated basic resources survey in the region should prove useful. Amiran (1973) has given some guidelines for the development of the arid zone. Following his suggestions, the developmental planning of the Indian coastal deserts may be recommended in the following order of priority:

(i) *Rangeland development and dairy-farming.* The existing permanent pasture lands and other available grazing-grounds should be fenced, and controlled grazing should be introduced.

(ii) *The development of mineral resources.* The available minerals, such as salt, bauxite, calcite and limestone, should be properly extracted. The modernization of the mines will increase the output and income per head. Investigations on soil and natural gas should be continued. The coastal areas of Jamnagar, and particularly the areas along the gulf of Kutch, may produce oil.

(iii) *Fishery.* The coastal area of the Gulf of Kutch contains good fishing-grounds. This particular industry has a good prospect in the Kutch and Jamnagar districts. Okha, Dwarka, Jamnagar, Gandhidham, Kandla port, etc. may become the centre of this industry. Proper investment to develop this industry is needed.

(iv) *Urban and industrial development.* The planning of urban development in the coastal arid zone should be considered from the following viewpoints: (a) the development of ports, e.g. Okha, Kandla and Dwarka, (b) the industrial development of settlements, e.g. Gandhidham and Jamnagar.

(v) *Tourism.* There are great prospects to develop tourism and its associated industries in this arid zone. Seaside resorts can be developed along the Gulf of Cambay and the Gulf of Kutch. The usually sunny weather and the scenic beauty of the regions may also help to attract tourists. The historical and architectural significance of places, e.g. Dwarka, may also help to develop tourism. The prospects of having a view of the desert and of the Rann of Kutch should provide much scope for the development of a viable tourism industry.

With the development of tourism, it is almost certain that the local arts and crafts will find avenues for fuller expression.

Game sanctuaries can also be developed in the Rann of Kutch area and in the Kutch District. The Rann of Kutch receives many migratory birds, e.g. the flamingo from coastal Africa, Asia and other countries. Other interesting birds, e.g. florican, imperial sand-grouse and *Houbara* are also found in large numbers.

Wildlife sanctuaries can also be developed in the area, particularly for the Chincara, the wild ass and the blue-bull. Jamnagar, and Okha can be developed as transport centres to visit the lion sanctuary in the Gir forest. Tourism and the resort industry have developed the economy of many coastal deserts in countries, such as Peru, Chili and Israel. There is enough scope to develop the Indian coastal desert, too, in this respect.

(vi) *Agriculture.* Agriculture is still the main occupation of the people. But owing to extremely arid conditions, high salinity, limited irrigational facilities and marshy land; it is doubtful how best it can be developed further. Dry farming techniques may be tried to develop agriculture. For the development of this coastal desert, as in other coastal deserts of the world (Amiran, 1973), agriculture should necessarily receive the lowest priority.

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11

LAND AND RESOURCE UTILIZATION IN THE ARID ZONE

H. S. MANN, S. P. MALHOTRA AND K. A. SHANKARNARAYAN

THE arid regions of India (including the cold desert of Ladakh) comprise about 12% of the total area of the country. The diverse problems imposed by aridity and the excessive biotic interference in the Indian arid zone have often been highlighted as thwarting any development measures in the region. However, the availability of the resources potential in terms of land, livestock, ground-water and vegetation is undeniable and it is now realized that the Indian desert, unlike others, is not so intractable as is often imagined. The major break-through lies in the planned exploitation of the resources based on scientific data, which could enable the optimum harnessing of the available resources. The prerequisite for formulating the strategies to utilize the land and other resources is to carry out an integrated resources survey in a comprehensive manner. The integrated surveys to assess the existing resources, their present use and the resource potential in the Indian arid zone for their rational utilization have been under way at the Central Arid Zone Research Institute for the last sixteen years. The present paper examines these aspects, with specific reference to the available resources, their present and the recommended use for optimum utilization,

LAND USE

The land-use data of 1970-71 (Table 1) reveals the respective percentages of forests, land not available for cultivation, other uncultivated land excluding fallow lands, fallow lands and the net area sown worked out at 1.58, 23.85, 19.30, 11.72 and 43.25.

The land-use data (Fig. 1) compiled for the period 1951-52 to 1973-74 for the twelve western districts of Rajasthan

Table 1. Land utilization (1970-71) in India and in the Indian arid zone

Area (million ha)

	Land-use category	India		The Indian arid zone	
		Area	%	Area	%
1.	Forests	65·9	21·54	0·53	1·88
2.	Not available for cultivation (Area put to non-agricultural uses + barren and uncultivable lands)	46·2	15·10	6·70	23·85
3.	Other uncultivated land excluding fallow lands (Permanent pastures and grazing lands+land under tree crops and groves + cultivable waste)	32·5	10·62	5·42	19·30
4.	Fallow lands (current fallows + others)	20·2	6·60	3·3	11·72
5.	Net area sown	141·2	46·14	12·2	43·25
	Total reported for land utilization	306·0		28·1	
	Total geographical area	328·0		31·9	

further indicate that land in this region is, by and large, unsuitable for crop culture and over 50 per cent of it is accounted for by current fallows, old fallows, culturable wastes and uncultivable barren lands.

Viewing historically it is observed that the percentage of the net sown area had been 28.61 in 1951, and 45.05 in 1971, whereas the percentage of the double-cropped area during this period ranged from 0.41 to 1.45 per cent only. The net sown area increased by 44.64 per cent during 1951-61 and by an additional 9.47% during *1961-71.* Barren, cultivable and uncultivable wastelands, permanent pastures and fallow lands declined by 16.83% during 1951-61 and further by 6.95% during 1961-71. Thus during 1951-71 there had been a significant decline in the grazing-lands due to the extension of cultivation of marginal lands.

The land-use capability classification forms an important criterion for assessing the resource potential of an area. The limitations, which primarily determine the land-use capability classes in the arid zone are the arid climate, the coarse sandy texture of the soil with very low water-retention capacity, proneness to severe wind erosion, duny physiography, effective soil depth and a high salinity hazard. Table 2 reveals that there are hardly any Class *I* or Class *II* lands in the arid region. Class III lands occupy about 27% of the area, Class IV lands 16 % and Class V lands about 1.2%. The Class VI lands predominate and account for as high as 45% of the area and they are

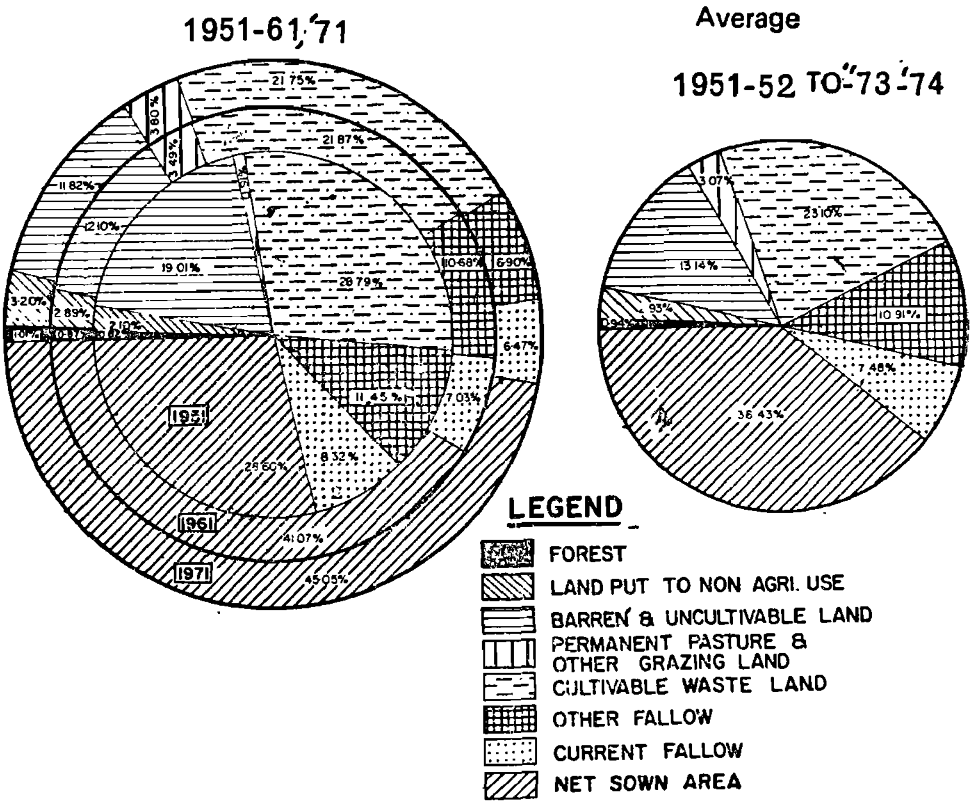


Fig. 1. Land utilization in arid zones

highly susceptible to wind erosion, particularly in less than 200-mm-rainfall zone. The rocky or saline lands occupy hardly 1.97 and 0.6% respectively.

Table 2. Land-use capability classes in the western arid region

Land-capability classes	Area (km^2)	Percentage of the total
II C*	333·0	0·70
III C	1,762·7	3 70
III C.W.	325·7	0·68
II X C e	8,691·2	18 25
III C, Sh.	2,086·6	4·38
II V Sa	23 1	0 05
IV C, e	7,456·3	15·66
IV C, Sh	221·4	0·46
V	88·4	0·19
V Sa. f.	501·1	1·05
VI E C	21,604·6	45·37
VII Sh, C,e	3,184·4	6 69
VII Sa	2·2	0 005
VIII Sa	285 8	0·60
VIII R	937·9	1 97
	47,504·4	

*C = Climate, Sa = Salinity, e = Wind erosion, W = Wetness, Sh = Shallow soil

The surveys conducted covering 64,140 km^2 (32.7% the arid Rajasthan) have shown that the present land use is inconsistent with the land-use capability dictated by the inherent soil characteristics. Investigations have revealed that only 46 to 60% of the area in the arid zone of Rajasthan is suitable for arable farming. The rest 21 to 24% of the area is made up either of dunes highly susceptible to wind erosion and hummocky plains or light-textured hardpan soil in danger of turning barren on account of surface stripping. This area should be put under permanent pasture for sustained production and resource conservation. Rocky pediments exposure which constitute 5.6 to 8.8 % are presently considered barren. They need also to be brought under permanent silvi-pastoral cover with a light grazing intensity. The capability-based, recommended land use, therefore, requires an increase under permanent pasture from the present 4.8–7.3% to 25–38% in the range districts of Jodhpur, Jalore and Barmer.

An area of 84,893 km^2 or 26.52% of the total arid area has been traversed either by reconnaissance, detailed reconnaissance, or detailed survey. About 90% of this area covers the 5 districts of western Rajasthan, namely Bikaner, Jodhpur, Jalore, Barmer and Nagaur. Based on the assessment of the land resources and their examination in relation to human resources, the climate and the present land-utilization, mapping-units or major land-resources units have been worked out on the basis of the units having the recurring pattern of biotic and abiotic environment. The units, thus framed, have not only a certain amount of environmental homogeneity, but have the same magnitude of problems and, therefore, the management practices to be adopted are likely to be the same within the units concerned. So far, 10 units have been tentatively standardized and their resources, present land use, nature and magnitude of desertification hazards and the recommended management are presented in Table 3.

POPULATION AND ECONOMY

The hot Indian desert is one of the most thickly populated deserts of the world having a population of over 19 million people and an average density of 61 persons (1971) per km^2, as against 3 persons per km^2 in most other deserts of the world. The growth rate of population in the region had been relatively high and the present demographic features show high potentialities of future growth of population (Malhotra *et al.*, 1972). The percentage of literacy in the region is low, being only 22.72 of the total population as compared with 29.34 per cent in the country. Apart from the other apparent reasons, the low percentage of literacy in the extreme arid areas (Rajasthan) may be attributed to the nomadic way of life of the people, nomadism being inversely related with the rate of literacy.

Table 3. Present land use, magnitude of desertification and recommended management in the major land-resource units of the western arid region

Major land-resource unit	Present land use	Nature and magnitude of desertification hazard	Recommended management
1. Flat aggraded older alluvial plain	*Kharif* non-cropping of mixture of *moth* and *bajra*, *kharif* pulses and oilseeds, e.g. *til*. The intensity of cropping varies according to rainfall conditions	In low-rainfall areas (200 mm), severe wind erosion hazard is highly conducive to desertification. In rainfall areas above 200 mm, the desertification hazard is medium	Single-cropped area to be managed by rational dryfarming techniques: (i) wind-strip cropping; (ii) stubble-mulching; (iii) windbreaks; (iv) water-harvesting.
2. Sandy undulating aggradable alluvial plains	Rainfed crops, such as *bajra*+*moth*	Moderate to severe wind-erosion hazard, having about 25 per cent lower fertility than ideally managed soil	To be developed for rangeland in blocks of 1,000 ha; fencing essential. After initial grubbing, to be reseeded with *Cenchrus*/*Lasiurus sindicus* @ 5–7kg/ha.
3. Flat inter-dunal plains	Rainfed mono-cropping, such as *bajra* and *bajra* + *moth* with long fallows of 2–5 years rotation	Moderate to severe wind-erosion hazard. Cultivation on marginal lands is a menace to soil. Wind-erosion hazard and the casting of sands in the adjoining lands	Farm forestry, runoff farming and development of rangelands, as per topographic location and micro-climate
4. Sandy undulating inter-dunal plains	Mono-cropping of low intensity, with long fallows ranging from 3 to 5 years	Same as above	To be developed for rangeland, farm forestry and runoff farming
5. Flood plain : (i) Narrow river in tracts	Often mono-cropping; but double-cropping on certain occasions under irrigated conditions	Wind- and water-erosion hazard—reduction of soil fertility	Requires a judicious cropping pattern; drainage control essential
(ii) Sandy complex-graded river-bed	Sandy waste-grazing for livestock	25 per cent to 50 per cent reduction in soil fertility	To be used for grazing, silvipastoral management needed
(iii) Duny area of aeolian complex	Low-intensity mono-cropping	More than 50 per cent loss in soil fertility	Development as rangeland; with *L. sindicus* and *C. ciliaris*
6. Sand-dunes : (i) Below 200 mm of annual rainfall	Cultivated only in years of good rainfall, otherwise wasteland (i) the base and the lower flanks are cultivated. Upper flanks and crests are grazing-land	Severe wind erosion, leading to 50 to 75 per cent reduction in cropped and plant population; degradation fortunately is not serious to develop range-management practices	Plantation of top-feed and fuel species in a phased manner in blocks of 1,000 ha or more. The reseeding of suitable grasses recommended on the windward side, flanks and crests
(ii) Rainfall above 200 mm	Wasteland comprises about 70 per cent. Base and flanks are cultivated and crests are sandy waste		

Table. 3. (*Contd*)

7. Mobile or active sand-dunes	Sandy waste	Highly affected, severe desertification hazards	Closure of the area for 10–15 years. Silvi-pastoral managements are recommended
8. Gravelly aggraded older alluvial plains	Gravelly waste to rain-fed mono-cropping grazing-land for live-stock	Moderately severe wind-erosion hazard, leading to about 25 per cent lower fertility than in the ideally managed soil	Water-harvesting and rangeland development
9. Eroded rocky lands	Stony and rocky waste grazing -land	Already desertified, practically lost 70–80 per cent of soil cover	Water-harvesting and catchment management
10. Saline depression	Saline waste-extraction of salt and gypsum	Highly desertified	Mining, rangeland development as post mining operations

Approximetely two-thirds of the total population constitute the non-working class. The high percentage of economically inactive population may be attributed to the high concentration of population in the lower age-groups. The occupational distribution (1971 Census) reveals that the respective percentages of workers engaged in the occupation of cultivation, agricultural labour and other occupations came to 53, 19 and 28. It may be observed that the percentage of workers engaged in the occupation of cultivation and agricultural labour combined is relatively high (72%) in the region. Animal husbandry is, however, often followed as a subsidiary occupation by the majority of the households and in certain pockets (where the aridity index is relatively high), such as the Anupgarh-Pugal region, it formed the main occupation of over two-thirds of the total workers (Malhotra *et al*, 1966). Another major occupation followed by the workers is the operation of household industries. The percentage of workers engaged in trade and commerce, transport and in other services is much lower.

AGRICULTURE

The data on the principal crops grown in the region (Table 4) reveal that *bajra* is the chief cereal crop produced and occupies approximately three-fifths of the total cultivated area under foodgrains. During 1970-71, the region produced about 6% of the total cereals and over 16% of the total pulses produced in the country.

The average size of the land holding in the arid zone of Rajasthan worked out at 9.9 ha, which is almost double the average size of the holding in the State. A lorenz curve (Fig. 2) drawn reveals the uneven distribution of land and the extent of concentration of land holding. Householders to the extent of 11.2% had

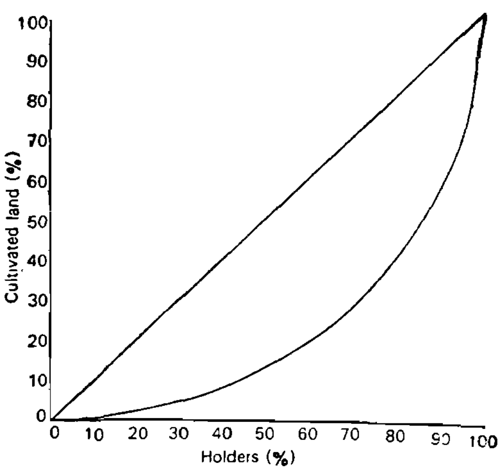


Fig. 2. Distribution of cultivated land in arid Rajasthan

Table 4. Area and production of principal crops for the year 1970–71

Crops	Indian arid zone			India		
	Area	Production	Yield	Area	Production	Yield
Rice	140·1 (1·03)	252 8 (3·53)	1 8044	37,592 (32·86)	42,225 (41·24)	1·1232
Jowar	809·6 (5·97)	331·8 (4 63)	0·4098	17,374 (15 19)	8,105 (7 92)	0 4665
Bajra	7,825·4 (57·71)	2,536 7 (35·41)	0·3241	12,913 (11·29)	8,029 (7·84)	0·6218
Maize	67·6 (0·50)	93·1 (1 30)	1 3772	5,852 (5·12)	7,486 (7·31)	1·2792
Wheat	1,232·5 (9·09)	2216·6 (30 94)	1·7984	18,241 (15 94)	23,832 (23·27)	1·3065
Barley	129·6 (0·96)	129·3 (1·81)	0·9976	2,555 (2 23)	2,784 (2·72)	1·0896
Gram	1,267·0 (9·34)	858·8 (11·99)	0 6776	7,839 (6 85)	5,199 (5·08)	0·6632
Other pulses	2,087·8 (15·40)	744·1 (10·39)	0·3564	12,040 (10 52)	4,736 (4 62)	0 3934
Total foodgrains	13,559·6	7,163·2		1,14,406	1,02,396	

over 50% of the total cultivated land, whereas 47.3% of the small farmers held only 10% of it. As a consequence of the increasing population, the small holders are making more and more constant use of the land for cropping, thus disturbing the earlier practice of leaving it fallow for replenishing its fertility. Therefore the overcrowding of the labour force on pre-modern agriculture has been resulting in the use of land beyond its ecological capabilities and its productivity has substantially declined.

Fig. 3 (a, b) represents area, production and productivity during 1954 to 1970 of the important crops grown in the arid zone of Rajasthan. It may be observed that the area under different crops and the production from them has increased, but the productivity per unit area has declined. The annual linear growth rate, i.e. the percentage of annual increase or decrease (1954-70) in the area, the total production and the productivity of different crops are presented in Table 5.

It may be observed that the area under important crops, e.g. *bajra* (pearl-millet), pulses and sesamum, shows an annual increase, whereas in respect of production only *bajra* shows an annual increase. The negative linear growth rate is mainly due to the bringing of marginal and sub-magrinal lands under cultivation, and this practice keeps on, and rather accelerates desertification,

The system of agriculture followed

Table 5. The annual linear growth rate of the area, production and productivity in respect of various crops (1954-70)

Crop	Area	Production	Productivity
Bajra	+2·41	+1·34	—0·66
Jowar	—3·41	—5 42	—4·88
Wheat	—0·82	—0·24	+0·60
Barley	—1 16	—0·05	+0 68
Gram	—6·31	—1·67	—1 59
Sesamum	+3·24	—3·57	—4·23
Other pulses	+1 91	—1·08	—2·70

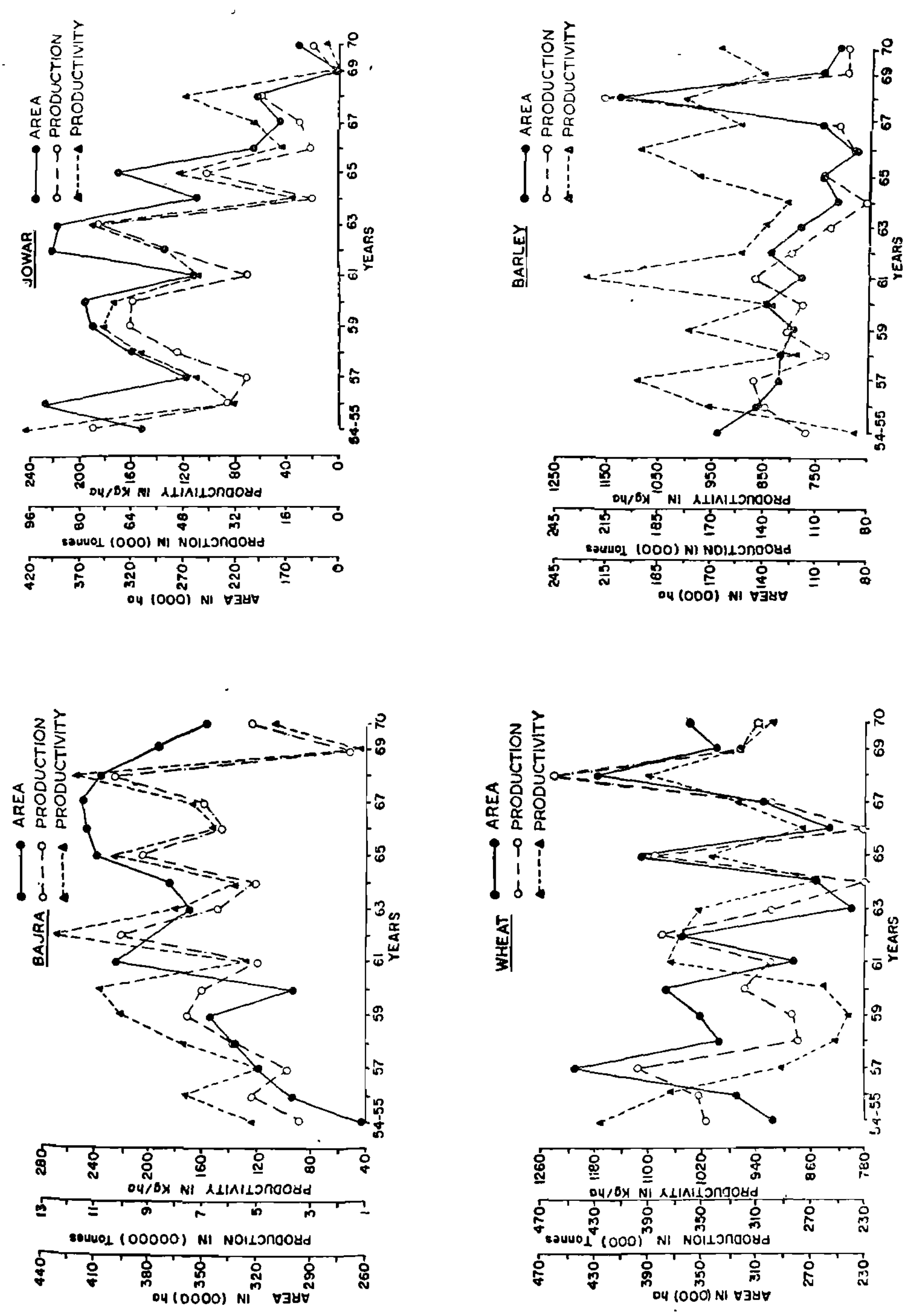
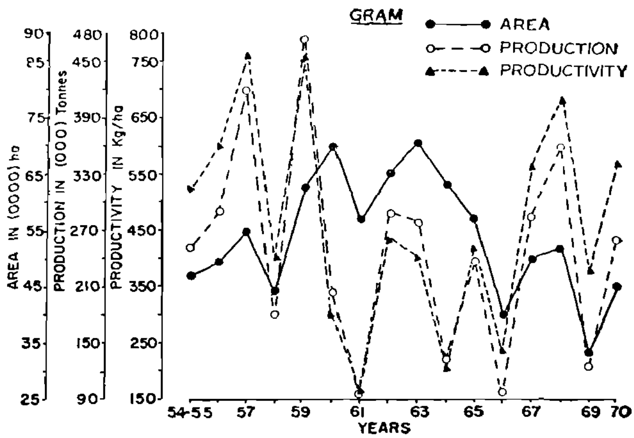


Fig. 3a Area, production and productivity of crops (1954–70)



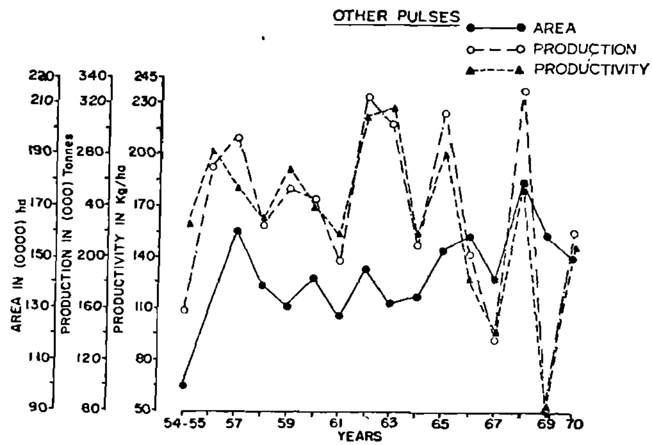
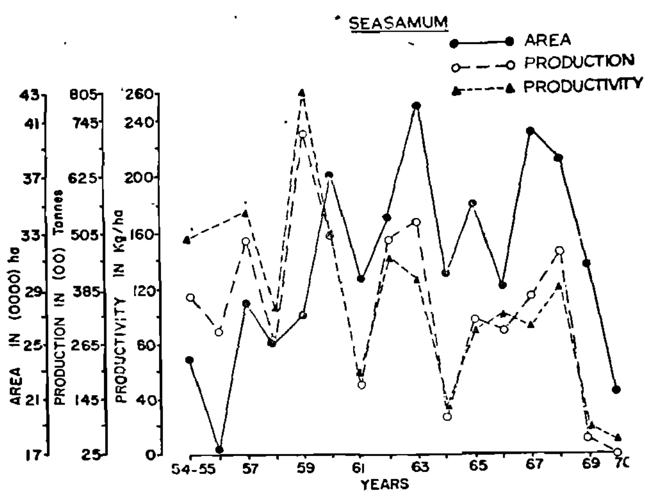


Fig. 3b Area, production and productivity of crops (1954–70)



indicates the *limitations* imposed by aridity. Subsistence farming is largely in vogue and it tends to make, the farmer security-oriented. This is an important cause of the low level of income. Low capital investment, labour-intensive agricultural operations, poor means of communication and inadequate marketing facilities impose further checks on efficient agriculture. The human effort to bring water up from the aquifers, which could be a factor in bringing about improvement and a built-in check on de-desertification, also present a dismal picture.

The data suggest that the irrigation (Table 6) in absolute as well as in relative terms, has been more or less static, ranging from 2.37% of the total area in 1966-67 to 4.25% in 1969-70. As regards the annual changes also, the desert region has been characteristically following almost a rhythmic pattern regarding rainfall. It thus seems certain that poor rainfall might have resulted in the poor recharging of the aquifers, leading to a reduction in the reported irrigated areas. Thus an insignificant area under irrigation, coupled with scanty, ill-distributed and erratic rainfall, fails to be a built-in process, efficient enough to increase productivity and arrest desertification.

It may, however, be worth while to add here that the available irrigation facilities could not only be much more effectively utilized and higher production achieved by the use of drip and sprinkler methods of irrigation (Singh *et al.*, 1973), but will also facilitate the use of highly saline waters (10 mmhos), commonly found in this region, for irrigation. Additionally, the introduction of the Rajasthan Canal shows a great promise and it is hoped that the region will achieve the status of a bordering region which came under the flow of the Gang Canal in 1927 and which is now not only a granary of the country, but also a good forest plantation.

The existing water sources and the Rajasthan Canal Project, when completed, will irrigate about 11% of the western Rajasthan, leaving about 89% as rainfed. The available technology for dryland.

Table 6. Irrigated area and its changes in the arid region of western Rajasthan (1956-73) including Ganganagar

Years	Total reported area ('000 ha)	Irrigated area ('000 ha)	Irrigated area as % of the total area	% Annual change (+ or —)
1956–57	21461	533·14	2·48	—
1957–58	21420	588·15	2·75	+10·32
1958–59	21363	595·65	2 79	+ 1·28
1959–60	21341	721·00	3 38	+21·04
1960–61	21314	649·02	3·05	— 9 98
1961–62	21360	733·86	3·44	+13·07
1962–63	21451	764·01	3·56	+ 4·10
1963–64	21348	844·56	3·96	+10·54
1964–65	21363	823·99	3·86	— 2·44
1965–66	21363	683·06	3 20	—17·10
1966–67	21361	506·65	2·37	—25·83
1967–68	21361	868·29	4·06	+71·38
1968–69	21377	839·23	3 95	— 3·35
1969–70	21377	903·90	4·23	+ 7 71
1970–71	21380	827·70	3·87	— 8·43
1971–72	21381	842·15	3·94	+ 1·75
1972–73	21376	895·55	4·19	+ 6·34
Mean ('000ha)	21,377 88	742·34	3·47	—
Changeover 1956–57 to 1973–74	—	—	—	—
S.D. ('000 ha)	34·66	129·18	0·61	—
C.V. (%)	0 16	17·40	17 45	—

management (Mann and Singh, 1975) suggest considerable potentialities in the arid areas through scientific land-soil-crop management. It may, however, be emphasized that adopting the technology of desert control and development has so long made only a small leeway among the farming community and steps for adopting them more quickly are essential. Studies (Malhotra *et al.*, 1974) on the relative importance of some socio-economic factors in the adoption of agricultural innovations suggest that it will be useful to encourage as much participation and involvement of the farmers in various activities as possible and to fully explore the ways and means to impart full knowledge of the innovations, as these two factors incline the farmers to a quicker adoption of them. It has further been found that in the propagation or diffusion of innovations the inter-personal communication along informal channels plays a far more important role than through the media of mass communication.

ANIMAL HUSBANDRY

Animal husbandry is the next important sector of agriculture. Table 7 indicates that cattle, buffaloes, sheep, goats, camels and other livestock constitute 7.30, 2.65, 6.86, 5.07, 0.65 and 0.19 millions respectively of the total 23 million livestock population. The livestock population exceeds the human population, the ratio being 117 head of livestock per 100 persons. The density of livestock which indicates pressure on the grazing-land is much higher in the region, being 1,022 head of livestock per every 100 acres of permanent pastures and grazing lands. In the context of the arid zone of Rajasthan it may be observed that the livestock population increased from 10.27 millions in 1951 to 16.44 millions in 1972.

Table 8 presents the number and com-

Table 7. The number of livestock for various regions of the arid zone of India (million–1966)

States	Cattle	Buffaloes	Sheep	Goats	Camels	Other livestock	Total livestock
Arid zone of Rajasthan	4·20	0·93	5·00	3·76	0·52	0·09	14 50
Arid zone of Gujarat	0·99	0·31	0·49	0·51	0·01	0·03	2 34
Arid zone of the Punjab	0·65	0 64	0·22	0·20	0 06	0·03	1 80
Arid zone of Haryana	0·42	0·37	0·20	0·17	0·06	0 01	1·23
Arid zone of Andhra Pradesh	0 68	0·30	0 77	0·31	—	0 03	2·09
Arid zone of Karnataka	0·30	0·09	0·16	0 10	neg.	neg.	0 65
Arid zone of Maharashtra	0 06	0 01	0 02	0·02	neg.	neg.	0·11
(Arid zone) Total	7·30 (32·13)	2·65 (11·60)	6·86 (30·19)	5·07 (22 32)	0·65 (2 86)	0·19 (0 84)	22 72 (100 00)
India	176·05 (51·21)	52·92 (15·39)	42·01 (12·22)	64·56 (18·78)	1 03 (0·30)	7·23 (2·10)	343·80 (100 00)

Table 8. The number of livestock (in millions) in the arid zone of Rajasthan

Livestock	1951		1956		1960-61		1965-66		1971-72	
	Number	%	Number	%	Number	%	Number	%	Number	%
Cattle	3·431	33 41	4·142	29·59	4·635	32·02	4·944	30·09	3·712	22·58
Buffaloes	0·775	7·55	0·826	5·90	1 030	7·12	1·218	7 41	1·167	7·10
Sheep	3·374	32·86	4·896	34·98	4·501	31·09	5 403	32·89	5·082	30 91
Goats	2·370	23·08	3·746	26·76	3·661	25·29	4·283	26 07	5·747	34·96
Camels	0·214	2·08	0·288	2·06	0·541	3·73	0·472	2·87	0·630	3·83
Others	0·104	1·02	0·099	0·71	0·108	0·75	0·109	0·67	0·101	0·62

position of livestock in the arid zone of Rajasthan during the different quinquennia from 1951 onwards.

It may be observed that of the total livestock, the percentage of sheep and goats ranged from 55.94 to 65.87 during 1951-72. Owing to recurring droughts and famines between 1967 and 1971, the number of cattle declined heavily (24.92% decrease) owing to huge mortality, whereas the number of hardy animals, e.g. goats, increased (34.18% increase) to a substantial level. This situation not only reveals the preponderance of goats and sheep in the total livestock population in the arid Rajasthan, but also the increase in goat population during the famine years. Of the limiting factors in improving sheep production in the arid and semi-arid regions, inadequate forage and drinking-water are resulting mainly from the improper use of resources.

The high pressure of livestock on the grazing-lands in view of their low carrying capacity results in the overuse of these lands resulting in depletion of the natural vegetation resources. The population has often to resort to migration and nomadic life for meeting the needs of their livestock. Studies (Malhotra, 1968) have revealed that each type of nomad community is associated with some kind of livestock which make an indiscriminate use of the meagre water available and grazing resources and nullify the local soil-conservation measures. The nomads in the present day are, thus, proving to be a menace to the whole society and their sedentarization is imperative and inescapable.

The grasslands and pastures (Ahuja and Mann, 1975) are valuable resources and mainly provide fodder and forage for the livestock. Research was, therefore, undertaken to establish the principles and practices of better pasture management to improve livestock productivity which also would contribute to the reclamation and development of the region.

VEGETATION RESOURCES

Owing to the harsh agro-climatic conditions, the region does not abound in a thick vegetation cover and, as mentioned earlier, the area occupied by forests worked out only at 0.8% of the total land. Champion (1936) has recognized the following principal types of vegetation in Rajasthan: (1) The northern desert thorn forest, (2) the northern *Acacia* scrub forest, (3) the northern *Euphorbia* scrub, (4) the inland dune scrub. Mathur (1960) further classified the above types and recognized the following: (1) The dry teak forest, (2) the *Anogeissus pendula* forest, (3) the mixed deciduous forest, (4) the tropical thorn forest, (5) the *Butea monosperma* forests, (6) the tropical thorn forest, (7) the subtropical thorn forests. Joshi (1956), Jain (1963), Nair and Joshi (1956), Shantisarup and Bhandari (1957), Shantisarup (1957, 1958), Satyanarayan (1963) and Satyanarayan and Shankarnarayan (1964) have conducted such investigations.

Owing to increased population not only has more land been brought under the plough, thereby reducing the number of trees and shrubs but also the increasing demand for wood has led to an unwise exploitation of the surplus vegetation sources. Trees and shrubs are put to multifarious uses by households, particularly for meeting the requirements of fuel-wood, housing, fencing, animal feed and for making ropes and baskets. For making agricultural implements, however, sometimes the timber is purchased, when the local resources prove to be inadequate for the purpose.

The requirement and the ever-increasing demand is huge and the overexploitation of the vegetal resources is inescapable. Most of the villagers in the rural areas procure firewood free from their own fields or from unoccupied lands. Digging *phog* (*Calligonum polygonoides*) is a regular vocation and gives employment to a large number of people and makes use of their camels when not otherwise occupied. The digging of the roots loosens the soil and accelerates wind erosion. Unless alternative sources for meeting the fuel needs are developed, the process is likely to continue and will add to the desertification of the area.

The rural population should be encouraged to plant trees around their habitations. The religious feelings of the womenfolk should be exploited by having small groves of *peepul* (*Ficus religiosa*) trees planted. It has been observed in the arid-zone villages that women pour water on the bases of the trunks of *peepul* trees at their own initiative, as this ritual is regarded as a pious act. Similarly, on the *oran* lands (lands left for religious temples), tree-plantation should be intensified, as the cutting of vegetation from these lands is religiously prohibited. The tree species, such as *Acacia tortilis*, *Dichrostachys glomerata*, are well adapted to the arid regions, with low moisture requirement and, hence, can be advantageously used for social forestry to meet the energy demands of rural inhabitants. Also there is ample scope for harnessing solar energy for its utilization in various ways (Garg, 1975). A low-cost solar water-heater and solar oven have been developed and if they are widely used, the shrubs and the trees can be spared to some extent and desertification can be partly checked. The use of the *gobar*-gas plants has also been well demonstrated in the area of the operational Research Project adopted in the Jodhpur District by the Central Arid-Zone Research Institute and, in addition to providing good manure, the plant will provide gas for fuel as bonus. It is hoped that the *gobar*-gas plant will get a good popularity in the region.

CONCLUSION

It may be observed that with the increase in the working force, the diversification in adopting occupations other than cultivation has not occurred, as the region lacks a diversified base. The available proven technology on dryland management suggests that enormous potentialities exist in the arid areas to transform the existing subsistence or deficit-oriented farming into that with marketable surplus through scientific land-crop management, consistent with the land-use capability and adoption of the recommended management practices for different land-resources units. Paradoxical as it may appear, there has been a shrinkage in grazing-lands, on the one hand, and an increase in the livestock population, on the other. This situation has led to excessive livestock pressure on grazing-lands and the people have often to resort to migration and nomadism for the survival of their livestock. Of the limiting factors in sheep production and animal husbandry in the arid region, inadequate forage and drinking-water are important because they impoverish the resources.

The high biotic interference has considerably influenced the occurrence and distribution of vegetation. Also, valuable cow-dung, otherwise an excellent manure, has been always wastefully used as fuel. These existing problems cannot, however, be solved through technology alone. Social action and awareness are essential. Historically, religions have adapted themselves to the changing economic conditions and it is inevitable that adjustments in outlook, compatible with basic religious beliefs, but more in keeping with economic demands, must take place, if the resources of the arid areas are to be fully used for the benefit of the people.

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12

WESTERN RAJASTHAN SOILS: THEIR CHARACTERISTICS AND PROPERTIES

R. P. DHIR

REGULAR surveys of some areas in western Rajasthan, aided by exploratory traverses in the rest of the State by various agencies, have furnished valuable data on soil distribution in the region. But the position of the soils in the major genetic classifications remains yet to be established.

Soils under an autonomous situation are devoid of any accumulation of significant soluble salts, with dominant E.C. 1:2 and pH values of 0.12 to 0.34 mmhos and 7.8 to 8.7 respectively. The distribution of alkaline earth salts, however, shows an interesting picture. The solum proper is often only moderately calcareous (0.2—5% $CaCO_3$). However, below the solum at depths of 40 to 120 cm, there starts a pronounced, often sharply differentiated zone rich in alkaline earth carbonates (5 to 45% $CaCO_3$ equivalent). Much of the free carbonates is present as well as defined, rounded, hard, crystalline concretions. This substrâtum is many metres thick. Roy *et al.* (1969) have attributed the occurrence of these strata to the ketamorphism in the weathered zone of igneous rocks. The process, according to them is geologically old, though it may be continuing even in present-day environment. This observation may explain the genesis of the zone of carbonate accumulation in peneplains, but for the vast alluvial plains, the principal process seems to be the redistribution and segregation of the alkaline earth sediments deposited along with the silicate sediments during a major alluvial activity under a seasonally dry environment. The results of analysis of some of these concretions (Table 1) show that calcium carbonate is by far the major constituent, followed by a small amount of magnesium carbonate. Some of these concretions were subjected also to radiocarbon dating which showed their ages to be 14,080 and 27,875 years B.P. For obvious possibilities of contamination, these dates may not be absolute, but these do suggest the ancientness of the formation.

Soils that have developed on wind-reworked sediments of major aeolian activity or recent alluvium are devoid of discernible pedogenic activity. While describing the monotonous character of the dune soil, Abichandani (1964) has indicated the occurrence of calcareous nests and crusts in the profile. The present author also observed a catenary sequence in the landscape with dunes and with a transect from the dune flank to the centre of interdune showing an increasing enrichment with silt, clay and carbonate (Dhir and Kolarkar, 1974).

Brief description of the major soils of western Rajasthan

The soils of western Rajasthan have been studied from the viewpoint of their classification. Raychaudhuri *et al.* (1963) described the soils of the area as 'Desert soils' and 'Gray brown soils'. Following Thorp and Smith (1949), Roy and Sen (1968) and Mathur *et al.* (1972) classified the medium-textured soils of the old alluvial plains in the 300–500-mm-rainfall zone as 'Sierozems' and those with a

Table 1. Dilute acid-soluble constituents of carbonate concretions of some arid-zone soils

S. No.	Location	Na_2CO_3	K_2CO_3	$CaCO_3$	$MgCO_3$	Insoluble silicate residue %
1.	Girab	0·55	Tr	82·40	1·35	14 4
2.	Dodo Hills	0·45	,,	74·15	0 95	21·5
3.	Jaisalmer	0·55	,,	76·00	3·80	20 9
4.	Jaisalmer	3·0	,,	48 25	3·10	45·9
5.	Pokaran	0·60	,,	88 05	5·20	3·9
6.	Pokaran	0·60	,,	85 15	2 45	13·2
7.	Bikaner	0·60	,,	85·45	3·15	10·2
8.	Jodhpur	0·55	,,	81 25	2 40	16 4
9.	Jodhpur	0·55	,,	82·50	2 95	11·2
10.	Jodhpur	0·55	,,	74 15	2·90	20·2
11.	Jodhpur	0 60	,,	84·50	1·35	14·5
12.	Jodhpur	0·55	,,	80 35	0·85	19·5
13.	Pali	0·60	,,	83·70	5·20	11·1
14.	Barmer	0·55	,,	81·25	0 80	16·2
15.	Jaisalmer	580·45	,,	65·20	2·0	33·9

less expressed structure in the 200–400-mm-rainfall zone as 'Red desert soils'. Light-textured soils of sandy plains were grouped as 'Desert soils'. These latter soils in the most arid part had earlier (Mathur *et al.*, 1968) been shown as 'Calcic brown desert soils'. Comparing the western Rajasthan soils with similar soils elsewhere, it appears that the former distinguish themselves by a lower content of organic carbon and a greater expression of alkaline earth content. The major soils recognized on the basis of profile characteristics are listed in Table 2. Also given is the placement of these soils in the USDA and the FAO systems of soil classification.

Brief description, together with laboratory characteristics are as follows:

Dunes are a dominant formation in 30.6% and a subdominant associate in 34% of the total area. They are

Table 2. Soils of western Rajasthan and their corresponding nomenclatures

Soils identified	USDA system	FAO/UNESCO
Dunes	Typic Torripsamments	Eutric Arenosols
Light Brown Sandy	Coarse loamy Typic Calciorthids Coarse loamy Typic Camborthids	Calcic Yermosels
Brown Light Loam	Coarse Loamy Typic Calciorthids	—do—
Grey Brown Loam	Fine loamy Typic Calciorthids Coarse loamy Typic Calciorthids	—do—
Hardpan	Coarse loamy Typic Paleorthids	—do—
Sierozem	Coarse loamy Typic Calciorthids Fine loamy Typic Camborthids	—do—
Recent Alluvial	Typic Torrifluvents (Coarse loamy, fine loamy)	—do—

N.B. All family names in the USDA system carry prefix mixed, hyperthermic.

mostly coalesced parabolic type, though longitudinal transverse and barchan types are also noticed. They are highly sandy, with 1.8 to 4.5% clay, 0.4 to 1.3% silt, 63.7 to 87.3% fine sand and 11.3 to 30.3% coarse sand (Table 3). Alkaline earth carbonate is largely present in a diffuse form, with a dominant range of 0.6 to 5.0%, though some in Barmer (Roy *et al.*, 1969) have been found to contain up to 15%. The dunes are devoid of any pedogenic features, except for a very weak segregation of alkaline earth carbonates as filaments or nests. Otherwise, the profile, exhibits a uniformly structureless, sandy mass with colour at different localities ranging from pale brown to brown (10 YR 6/3, 5/3, 5/4 D). The dune landscape has some accumulative interdunes with 2.9 to 12.3% clay, 2 1 to 16.5% silt and 1.5 to 29.9% free alkaline earth carbonates.

Table 3. Mechanical composition and other characteristics of the arid-zone soils

Depth	pH	E.C.1 : 2	Clay	Silt	Fine sand	Coarse sand	$CaCO_3$ equivalent	Alkaline concretions	C.E.C. me/100 g	Organic carbon %
					Dunes					
0–15	8·8	0·07	4·2	0·7	81·6	13 4	5 4	Nil	2·9	0·11
15–30	8·6	0.07	4.1	0.9	83.8	11.2	4.8	”	2.7	0·09
30–60	8·6	0·06	4·3	0·8	84·2	9 8	5 1	”	N.D.	0·07
60–90	8 5	0 06	4·4	1·4	83·1	10·6	4·9	”	”	0·07
90–150	8·6	0·06	4·6	0·8	83 5	11·3	5·5	”	”	N.D.
150–210	8·5	0·07	4·4	0·9	81·8	13·1	6·6	”	”	”
0–20	8·4	0·08	5·2	0·9	77·2	16·4	3·2		3·3	0·09
20–45	8·4	0 07	5·1	1·3	77·5	15·8	4·2		2 9	0 07
45–90	8 3	0·07	5·3	1 1	77 4	16·7	4·0		2·8	0 04
90–135	8·3	0·08	4·8	1·5	76·0	17·3	5·3		2 6	0·04
					Light-brown sandy					
0–15	8·2	0·09	6 1	4·3	77·8	11·2	1·3	Nil	4·1	0·16
15–40	8·5	0·12	7·0	4·5	77·7	10 6	3·6	”	4·0	0·13
40–120	8·5	0·13	8·8	4 8	74·8	8·2	8·7	1·3	4·2	N.D.
120–190	8·6	0·16	8 4	4·0	74 3	13 2	6·4	6·4	4·0	”
190–300	8·6	0·16	9·4	5 3	74 0	10·8	7·2	4·8	4·4	”
					Brown light loams					
0–15	8·2	0·13	10·4	5·9	73·1	9·6	0·3	Nil	6 9	0·28
15–40	8 3	0·14	13·8	7·3	70·5	8 2	0·3	”	7·2	0·24
40–75	8 3	0·14	14·4	7·5	70·0	8·0	2·1	0·1	7 1	N.D.
75–90	8·7	0·18	12·8	8·3	70·6	7·9	7·8	10·6	6·8	”
					Grey-brown loams					
0–15	8 3	0·24	18 4	12·2	55 0	14·2	0·8	Nil	12 3	0·38
15–60	8 5	0·27	22·6	13·8	49·8	13·6	1·3	”	12·0	0·30
60–100	8·6	0·35	19·3	12·6	55 3	12 8	18·6	18·4	10 2	N.D.
100	8·8	0 54	18 3	10·5	57·4	13·9	14·2	9·3	10·0	”
0–12	8 3	0·31	25·4	13·7	50 5	10·2	1·3	Nil	17·2	0·45
12–25	8·5	0 37	28·1	12 4	50·0	10·0	3·7	”	19·0	0·40
25–65	8·5	0 41	28·7	11·7	52·2	8 3	5·8	1·3	18·8	N.D.
65–90	8·7	0·73	28·2	13·6	48·3	9·6	15·8	15·8	17·3	”
90+	8·8	0·57	31·3	13·2	43·7	10·5	14·3	17·3	16 8	”

Light brown sandy soils, associated respectively with a few to many dunes, occur in 34 and 30.6% of the area. The soils are characterized by a varying hummocky surface (3.6 to 6.2% clay, 1.8 to 3.1% silt), very weakly blocky loamy fine sand, dominantly brown (10 YR 5/3 D), sometimes pale-brown (10 YR 6/3), weakly calcareous subsoil, followed at 80 to 120 cm by a weakly to moderately developed zone of alkaline earth carbonates (Plate **d**). The calcium carbonate concretions form 3 to 25% by weight and, besides their diffused form, another 5 to 10%. Within this dominant picture are found sizeable patches, apparently associated with old drainage lines of soils which have heavier texture and a massive concretionary stratum of calcium carbonate.

Brown light loams have prolluvium and alluvium derived from fine-grained sandstone as their parent material. The soils occupy 1.7% of the area and are characterized by loamy fine sand to fine sandy loam, brown, weakly blocky surface, a slightly heavier, darker (10 YR 5/4 D), calcareous subsoil, followed at 40 to 90 cm by a zone of lime concretions.

The grey brown loams occupy 13.6% of the area and occur in the alluvium and weathering zone of medium and fine-grained sedimentary rocks in the south-eastern and central parts. These soils are devoid of wind-worked deposits and have apparently escaped the deflation breakdown experienced on other landscapes. Soils deflation are dark greyish brown to brown (10 YR 4/3, 4/3, 5/3 D), moderately subangular blocky, sandy loam to loam on the surface. The subsoil is heavier with a well-developed sub-angular blocky structure. It is followed by a zone of calcium carbonate as concretions and as coatings on gravels (Plate **e**).

Soils with hard pan (5.9%) are brown (10 YR 5/3, 5/4 D), generally light-textured, with a hard, largely indurated pan at depths of 40 to 80 cm. At places, the hard pan is close and even exposed. The major area of the soils is located in the central part, though small pockets are scattered throughout. The thickness of the indurated horizon is more than a metre thick and it is formed by a calcium carbonate cementation of gravels and concretions. The stratum is slightly permeable to water and difficult for plant roots, particularly for useful top-feed species, the growth of which is severely restricted.

Sierozems (1.6%) are a southward extension of a much larger occurrence in the neighbouring Haryana and Punjab States. These soils are developed on the alluvium of the Ghaggar and allied streams. The soils are brown to light brownish grey (10 YR 5/3–6/2 D), often moderately calcareous, very fine loamy sand or finer with a moderately developed blocky structure. At depths of 60 to 120 cm is a weekly to moderately developed zone of concretions of calcium carbonate.

The alluvial soils with dunes (6.8%) are of recent origin and are devoid of any appreciable pedogenic activity, except for some structure formation and some redistribution of alkaline-earth carbonates. The profile is often stratified with large variations in particle size. Soils in the north-west are often saline sodic and calcareous. They are interspersed with dunes and hummocks. Besides these, hills and pediments, often partly buried under sand (Regosols and Lithosol), form another 5.6%. There is a small area under saline depressions.

SOIL FERTILITY CHARACTERISTICS

Clay mineralogy. Krishnamurti and Narayana (1968) studied soil profiles from seven localities in the rainfall zone of 450 to 170 mm and a summarized form of their results is given in Table 4.

This finding shows that illite is the predominant mineral in all soils. The grey brown loams are the only exception where montmorillonite dominates and this condition was attributed by the authors to advanced weathering under a higher rainfall. Attapulgite has not been reported from any Indian soil, whereas it is present in all the arid-zone soils, except in these in the 450-mm-rainfall zone. Table 5

Table 4. Clay mineralogy of the arid-zone soils

Soil group	Rainfall in mm	Mean clay mineral composition in %			
		Montmorillonite*	Illite	Kaolinite	Attapulgite
Grey-brown loams (1)	450	60	25	10	—
Light-brown sandy soils (4)	280–350	25	52	10	13
,, 2	170	20	50	10	20

*Non-expanding type, except on the surface of grey brown loams

gives the C.E.C. values of the clay fraction of some soils in the arid zone from the work done in the Pedology and Survey Section of the CAZRI, and these values also suggest the dominance of an illite-like mineral in the soils.

Table 5. The cation-exchange-capacity values of clays in some arid-zone soils

	Number of samples	Range	Mean
Dunes	4	36–45	42
Light brown sandy	12	38–49	43
Brown light loams	10	38–52	45
Grey brown loams	24	45–70	61
Recent alluvium	6	38–45	42

Organic matter. Jenny and Raychaudhuri (1960) during an excellent study have brought out the effect of climate and cultivation on the nitrogen and organic-carbon status in the soils. They have also emphasized the role of texture. In Fig. 1 are plotted the data on organic carbon in relation to the clay content. The results show that with the rising clay content, there is a sharp rise in the organic-carbon content and that the soils in the 300–450-mm-rainfall zone have a slightly higher content than the soils in the below 300-mm zone. Aggarwal and Lahiri (1976), while bringing out the low organic carbon of the dune soils, in general, have shown a difference owing to the degree of colonization by vegetation. They found that whereas the bare dunes had around 0.03% organic carbon, the vegetation-stabilized dunes had 0.1%. The former, however, had 70 to 100 ppm of mineral nitrogen, whereas the latter had only 45 to 65 ppm of it. Aggarwal *et al.* (1975) have also found that in a 300–400-mm-rainfall zone, the C/N ratio varied from 7.9 to 13 in the surface soils and from 3.9 to 7.2 in the subsoil. Their results also showed that among the various nitrogen fractions, amino acid and unidentified fractions dominated. The mean percentage values for the amino acid (unidentified), ammoniacal and hexasamine fractions were 18.8 to 40.0, 14.1 to 50.0, 3.1 to 9.4 and 0.8 to 3.1% respectively. Comparing the results with those of other tropical soils, the authors found a higher relative concentration of the amino-acid fraction in the arid zone soils.

Phosphorus. Ram Deo and Ruhal (1972) reported that light-textured soils of the arid zone had 285 ppm of total phosphorus as compared with 327 to 450 ppm in the soils of the semi-arid zone of Rajasthan. Pareek and Mathur (1969) also reported comparable values in respect of the arid zone soils. In the extreme north-west, the soils developed from the Indus and the Ghaggar alluvia were found to have higher values of 408 to 716 ppm of phosphorus (Talati *et al.*, 1975). Phosphorus occurs in a variety of forms, fixed with varying intensity, to the individual soil constituents. The above studies also showed that 40 to 50% of total phospho-

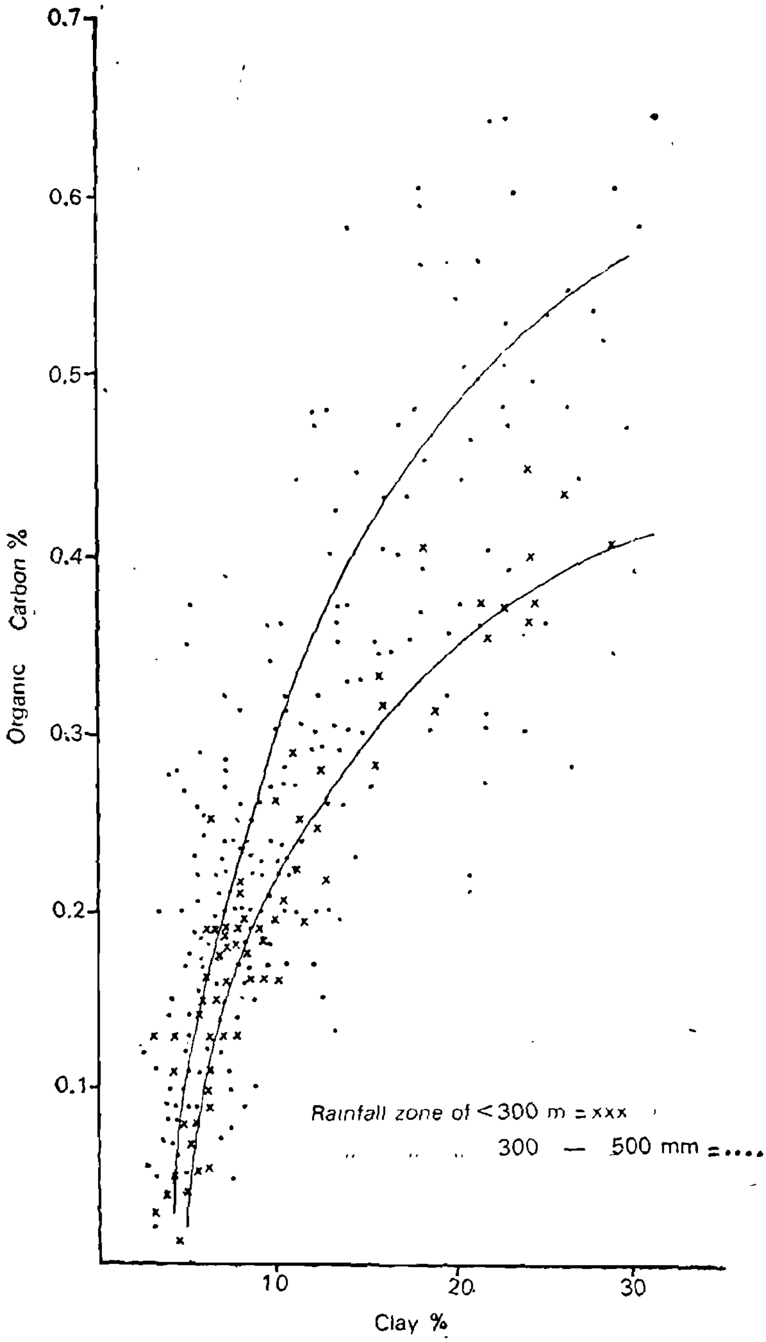

Fig. 1. Distribution of organic carbon content in relation to clay percentage in arid zone soils

rus in the arid-zone soils, in general, and up to 72% in the Ghaggar alluvium soils is bound with calcium. This fraction is proportionately more in the arid-zone soils than in the adjoining soils of the semi-arid zone. However, these soils still contained appreciable amounts of aluminium and saloid-bound phosphorus, which have been found (Ram Deo and Ruhal, 1972; Sacheti and Saxena, 1973) to be correlated with the available phosphorus content. This condition may explain the presence of a fair amount of available phosphorus in the arid-zone soils, despite soil calcareousness. The results of available phosphorus status of the arid-zone soils are dealt with elsewhere in this paper. The amount of added phosphorus that becomes available to plants is dependent upon the fixation capacity of the soil. Dhawan *et al.* (1969) showed that the arid-zone soils fixed 0.87 to 1.35 g, with an average 1.053 g of phosphorus per 100 g of soil, and this amount was quite high. However, Ram Deo and Ruhal (1972) found that the buffering capacity or the amount of phosphorus that needs to be added for a unit increase in intensity in the arid-zone soils was less than half that found in the adjoining soils. This situation is advantageous, since a smaller amount of phosphorus will be needed to raise its concentration in the labile pool and also that even lower values of phosphorus in the soil will be adequate for a good growth of crops.

Potassium. Soils of the arid zone are generally well supplied with potassium. Dhawan *et al.* (1968) and Chaudhri and Pareek (1976) have shown that with the exception of a few localities, the total potassium is between 825 and 1890 mg/100 g of soil, and this amount compares favourably with the mean value of 806 mg/100 g of the Rajasthan soils as a whole. Water-soluble and exchangeable potassium together form 1.5 to 2% of the total potassium and, therefore, by far the major proportion is present in a non-exchangeable fixed form or partly as a primary mineral lattice. The reserve potassium which gives the soil a capacity to withstand depletion, constitutes 8 to 15% of the total. Lodha and Seth (1970) and Chaudhri and Pareek (1976) found that the reserve potassium and the total potassium are correlated with the silt and sand fractions respectively in the soil. This finding, together with mineralogical composition, reported earlier shows the presence of large potassium reserves in the arid-zone soils. Besides, the potassium-fixing capacity (Lodha *et al.*, 1976; (Chaudhri and Pareek, 1976) has been found to be lower in the arid-zone soils than in those outside, largely because of the lower clay content of the soil.

Micronutrient status. Seth *et al.* (1971) found that the total manganese content in the arid-zone soils ranged from 212 to 437 ppm. Of this amount, on an average, 32 ppm and 6 ppm were in the reducible and available forms, respectively. Mondal (1965) also reported similar values in respect of the arid-zone soils. The values of reducible and available forms were lower than those of the soils outside the arid zone, though adequate for plant nutrition according to the existing criteria of 20 and 5 ppm respectively. Sand-dune soils are seen to have lower contents of available and reducible forms than other soils.

Copper. The total copper content of the soil profiles at Jodhpur varies from 10 to 11.5 ppm (Mondal, 1965) in all the layers up to 170 cm. Seth *et al.* (1971) reported that the total copper content of the Rajasthan soils ranges from 19.6 to 228.48 ppm, with a lower value (64.99 ppm) for desert soils. The available copper varies from 0.21 to 4.28 ppm and, in general, the arid soils are not low in this element. However, Lal and Biswas (1973) reported 0.12 to 0.28 ppm of available copper in the Rajasthan soils.

Zinc. Seth *et al.* (1971) and Lal and Biswas (1973) observed that the total zinc content ranged from 5.0 to 95.2 ppm and the available zinc from 0 to 4.83 ppm in the Rajasthan soils. On an average, 2.07 ppm of available zinc had been reported in the arid soils, and this amount is sufficient for normal plant growth as per accepted norms.

Iron. Mondal (1965) reported a decrease in the water-soluble iron content with the depth from 0.95 ppm for the 0-20 cm layer to 0.03 ppm in the surface layer below 170 cm. Lal and Biswas (1973) observed the available iron to range from 0.3 to 5.6 ppm in the Rajasthan soils and it was low (2 ppm) in the desert soils.

Boron. The water-soluble boron in desert soils varied from 1.9 to 12.2 ppm (Satyanarayan, 1958) and slightly increased with the depth. Seth *et al.* (1971) reported that the boron concentration in the desert soils, undifferential alluvium and grey brown soils of the river basin, in general, was higher (0 5 to 8.2 ppm) than the safe limit. They observed a significant correlation of available boron with pH, but the organic carbon and $CaCO_3$ contents of the soils were not related with it. Nathani *et al.* (1970) also observed similar ranges for the Rajasthan soils.

Sulphur. The total sulphur content of sierozems, alluvial and desert soils appeared to be higher (Joshi *et al.*, 1973). This higher content may be attributed to the inorganic forms. In desert and sierozem soils, the organic sulphur content ranged from 50-180 ppm (30-50% of the total sulphur). Sulphur in the sulphate and non-sulphate forms were highest, up to 200 ppm, in the arid soils when compared with 70.160 ppm in the adjoining soils and constituted the major part of the total sulphur. The available sulphur content of the desert soils ranged from 40 to 133 ppm. Joshi *et al.* (1973) and Joshi and Seth (1975), while working to determine the interaction between sulphur and phosphorus in the soil and in the mustard and wheat crops indicated that there was an increase in the available sulphur and available phosphorus contents of the soils due to the application of sulphur to all loamy-sand soils. But a higher sulphur uptake depressed the P uptake. The most effective S/P ratio for the mustard and wheat plants were between 0.9 and 1.4 and between 0.71 and 0.85 respectively.

The salinity-alkali problem. Though the ground waters and substrata contain a large concentration of dissolved salts, salinity in the solum proper is fortunately a localized feature. Its occurrences are associated with (i) the natural salt basin and playas, (ii) the flood plain of the Ghaggar and the Luni systems, (iii) the closeness of the saline-sodic waters due to the recent tampering with the natural drainage, and (iv) irrigation with highly saline waters. The approximate area occupied by each of these areas is as follows (Table 6).

Table 6. Saline-infested areas

	Area in sq. km	% of the total area of western Rajasthan
(i) Major salt basins	431	0 22
(ii) Flood plains of the Ghaggar and the Luni river systems	2434	1·24
(iii) Salinity due to the recent rise in saline ground waters	559	0 28
(iv) Irrigation with saline sodic waters	1722	0·88

Of these, salinity due to the use of saline water is by choice, since the system has some distinct advantages which outweigh the limitations. Some of the salt basins serve as a major industry. In the other two categories, salinity is a problem, particularly since either the area falls in the command of the ongoing irrigation projects or had once been productive or deteriorating. Considerable work has been done in characterizing soil salinity. The analysis of 205 soil samples (the Rajasthan Department of Agriculture, Agricultural Chemistry Section, 1970-71) showed that 26 3, 20.1, 17.5 and 36.1 per cent of soil samples had E.C. of the saturation extract less than 4, 4 to 8, 8 to 12 and over 12 mmhos respectively. The analysis of 103 samples collected during the soil survey of the Bikaner District by the CAZRI also showed high salinity in the flood plain as well as in the playas. In all, except 9% of the samples, salinity was of sodium chloride or sulphate type, with nearly 33 per cent showing significant quantities of calcium sulphate. Mehta *et al.* (1969) have analysed the reclamation problems of these soils and have showed the scope of leaching, amendments and the use of fertilizers in well-drained situations.

THE AVAILABLE NUTRIENT STATUS

Since the establishment of the soil testing service as part of the farmers' advisory programme of the Rajasthan State Department of Agriculture, valuable data have been built up on the soils of the arid zone.

Results of these activities are presented in Tables 7a, 7b and 7c. The results show that by far the majority of the arid-zone soils test low in organic carbon or available nitrogen. As regards potassium a negligible percentage of samples falls in the low category, the rest being in medium or high categories. Concerning phosphorus, the picture is variable. Whereas in some areas, the soils are dominantly low in phosphorus, in others they are medium or even high in this element.

Moisture-retention and conservation properties

The field-capacity values of soils, as measured from the moisture equivalent, show as vast range from 3.3% by weight in the dunes to as high as 25% in some of the grey brown loams. Kolarkar and Singh (1971) have shown the dependence of this property on the clay plus silt content of the soils. Besides, the total moisture retained in the soils depends on the soil depth, as limited by the presence of hard pans, which are often somewhat pervious to water, but less so to the roots of annual plants. In some playas soils, the low intake rate limits the entry of the rainwater itself.

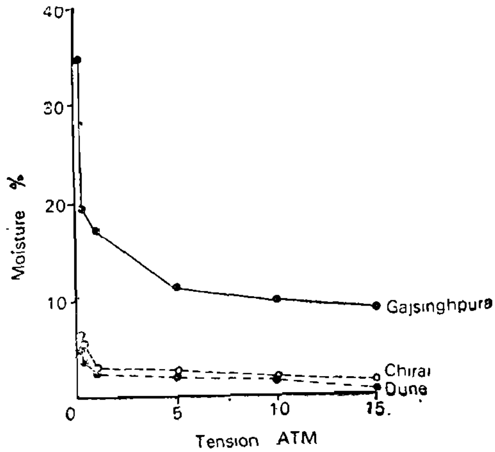

Fig. 2. Soil moisture-tension relationship of some soils. Chirai and Gajsinghpura soils belong to light brown sandy and grey brown loams respectively

The light-textured soils, whereas having low retention, have the ability to make

Table 7a. The available-nutrient status of the soils in the surveyed areas (CAZRI)

Block	The number of samples	Organic carbon			Available phosphorus			Available potassium		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Saila	179	84 5	7·1	8·4	56·2	35·6	8·2	11·0	59 3	29·7
Ahore	65	84·6	10 8	4 6	79 4	20·6	—	—	41·2	58 8
Chohtan	18	100·0	—	—	94·1	5·9	—	35 3	35·3	29·4
Balotra	24	87·5	4·2	8·3	50 0	29·2	20·8	4·2	37 5	58·3
Jalore	104	88·9	10·2	0·9	51·3	43·3	5 4	28·2	46·2	25·6
Luni	102	96 2	3·8	—	37 1	59·1	3·8	20 0	75 8	4·1
Bikaner District	75	98·7	1·3	—	41·8	41·8	16·4	4·0	52 0	44·0
Jodhpur District	402	97·8	1 5	0 7	56 6	40 1	3·3	23·3	70·7	6·0

Table 7b. The available nutrient status of the major soils (Sanghi *et al.*, 1976)

Soil group	The number of samples received and analysed	Organic carbon			Available P_2O_5			Available K_2O		
		L %	M %	H %	L %	M %	H %	L %	M %	H %
Desert calcic brown soils	144	89 10	7 90	3 00	25·13	44·43	30·44	23 60	50 70	25·70
Desert soils	4912	88 30	7 40	4 30	23 00	46·10	30 90	2 10	59·90	38 00
Grey-brown alluvial soils	12695	80·60	11·10	8·30	22 50	38 80	38 70	14 70	35·20	50·10
Brown soil (Saline phase)	2709	89·30	3·80	6 90	26 30	38 30	35·40	21 10	38·10	40·80
Non-calcic brown soils	1543	79 00	15·70	5 30	2 50	80 50	17 00	5 50	78 50	16·00
Hilly soils	2250	72·50	13 10	14·40	30·84	26 84	42 34	15·16	42 15	42·69
Total	24,253	82·33	10 00	7 67	22 54	41·80	35 66	12 37	44·02	43 61

Table 7c. Criteria for Tables 7a and 7b

Nutrient	Low	Medium	High
Organic carbon %	Below 0·5	0 5—0 75	Above 0 75
Available phosphorus (as P_2O_5 in kg/ha)	Below 22 4	22 4—56	Above 56
Available potassium (as K_2O in kg/ha)	Below 140	140—336	Above 336

Table 8. Particle-size distribution and wind-erosion manifestations in soils under arable farming

Soil group	Depth in cm	Clay %	Silt %	Sand fraction %						Wind-erosion features
				mm ·02- 05	mm ·05-0·1	mm 0 1-0·2	mm 0·2-0·5	mm 0·5-1·0	mm 1·0-2 0	
Dune soil	0–30 30–60	3·3 3 2	0 8 1·4	0 3 0 4	19·8 18 3	60 8 64 4	11 3 8·7	2 1 3·3	0·7 0 3	Very highly hummocky
-do-	0–30 30–60	2 8 3·0	0·9 1 0	1 8 0 9	11·2 8·8	65 4 66 3	12 7 15 3	4·5 4·5	0·7 0 0	,,
Light-brown sandy soil	0–25 25–60	5·9 8·2	2·6 4·8	1·8 2 4	13 6 11 4	57 9 53·8	17 4 17 2	2·1 1·4	0 7 0 2	Highly hummocky
-do-	0–20	9·51	6 0	11·7	27·7	35·2	8·3	1·3	—	Few hummocky with vivid fence-line deposition
-do-	0–20 20–40	7·99 10·50	6·16 6 82	3 29 2·81	21 97 20·10	47.32 50·20	6·61 5·7	4·20 3·10	0·30 0·20	,, ,,
Brown-light loam	0–15 15–32	10·2 17·2	6·5 4·8	5·5 5 0	16 0 15·3	21·1 23 0	34·8 33·8	3·5 3 6	Nil Nil	Vivid fence line deposition, and occasional hummock
-do-	0–25 25–60	13 70 15 40	5·94 7 20	8·60 6·99	30 40 27 10	28 40 25·30	7·57 8·91	5 97 7 64	0·0 0·0	Slight fence line deposition
Grey brown loam	0–15 15–35	11·70 16·90	10 0 10·3	9·70 9 10	22 60 20 00	20 00 19 80	8·20 7·10	12 8 8 4	0 82 0 48	No discernible features
-do-	0–20 20–45	16·20 19·10	7·50 10 10	10·70 9·50	19·80 18 00	18 70 22·90	9·10 12·70	1·20 1·80	0·22 0·00	,,
-do-	0–15 15–40	15 50 23·80	11·30 16·70	10 80 9·20	28·10 19 80	25 40 20·10	2·80 1·80	0 60 0·30	0 02 0·00	,, ,,

Table 9. The nature and magnitude of land limitations in surveyed areas

Nature of limitation	Applied significance	Percentage of the area affected			
		Bikaner	Jodhpur	Jalore	Barmer
Area surveyed in km^2		27,336	22,640	3,978	5,215
Severe wind erosion and the occurrence of dunes	Massive loose sand interferes with the establishment and maintenance of a good stand of annual and perennial vegetation; some loss of soil fertility	45.1	13.1	13.6	47.1
Severe wind erosion with highly hummocky relief	Same as above, only slightly less severe. Under arable farming, intense conservation measures are necessary for erosion control	22 6	32 6	22·0	12 7
Moderately severe wind erosion and shallow soil depth	Continued erosion severely threatens land productivity. The establishment of pastures possible and lands ideal for them	7·1	15 4	0 2	—
Shallow soils, rocky outcrops and barren hills	Almost denuded, need conservation through permanent vegetation cover. Permit light grazing	0·6	7 6	12·2	9·7
Severe wind erosion and moderate water erosion on sand-covered piedmonts	Loss of fertility and gully formation. Discontinuation of cultivation and improvements of pastures necessary	Neg.	0 3	6·3	—
Salinity hazard due to the nearness of saline-sodic waters	Lands already affected. Improvement of natural drainage necessary	—	0·7	7 7	1·2
Natural saline depression and recent, saline flood plains	Lands already affected. In some situations, reclamation possible with freshwaters	1·3	0·8	—	1·3
River-beds, etc. Water erosion, some salinity	Some improvements possible with management	0·1	0 4	3·2	1·2
Moderately severe wind erosion, a few hummocks	Some loss of soil fertility and moderate difficulty in crop establishment. Farming possible with simple soil-conservation practices	23·2	19·7	21·2	24 6
Negligible wind erosion	Arable farming possible, climate is the only limitation	—	9·4	13·8	0·8

available the bulk of the stored moisture, as may be seen from the moisture-release curves in Fig. 2 (Courtesy, Dr H.P. Singh, Soil Physicist).

The light-textured soils have also the property of conserving moisture in face of strong atmospheric moisture deficit, amounting to over 2,000 mm per year. Abichandani *et al.* (1967) observed that such a soil kept as a bare fallow lost only 67 mm of the stored moisture during the year. Out of this amount 75% loss was from the top 30 cm and the soil below 30 cm remained close to the field capacity throughout the year.

Aggregation and erodibility

The author's observations on a light-textured soil, having 7.4% clay and 6.2% silt, show that upon sieving for two minutes, it had 8.9∓2.2% soil mass in aggregates over 5 mm, and 16.7∓ 4.1% in aggregates over 2 mm. In comparison, the dune soil, with 3.2-4.5% clay and 1.1-3% silt was devoid of such an aggregation, indicating the significance of a small increase in fine particles. The importance of soil texture in imparting stability against wind erosion was also seen in the absence of hummocks and the piling up of loose sand in certain soils. The results of such observations on lands under rainfed farming for many decades are given in Table 8. With the clay content over 15%, the erosion features totally disappear. The only exception is a soil with an extraordinarily high amount of particles over 0.2 mm. In that soil, in spite of a higher clay content, fence-line hummocks are seen.

THE NATURE AND EXTENT OF LAND HAZARDS

Wind erosion is particularly more damaging where the soil depth is already a limitation because of the closeness of the hard strata, and the arid zone has a significant area of such soils. Table 9 gives an indication of the extent of the area affected by various limitations in some of the districts surveyed. The results show that wind erosion is by far a major hazard.

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13

GEOMORPHOLOGY, SOIL AND LAND USE IN DESERT REGIONS OF GUJARAT, PUNJAB AND HARYANA

R. S. MURTHY AND S. PANDEY

ALTHOUGH a major part of the hot Indian desert falls in the west of the Rajasthan State, the adjoining areas of the States of Gujarat in the south and the Punjab and Haryana in the north also form the constituent parts of the desert. According to Krishnan (1969), the Gujarat part consists of 62,180 km^2, i.e., nearly 20 per cent of the total desert area of the country, extending to the districts of Banaskantha, Surendranagar, Rajkot, Kutch and Jamnagar. Deserts occupy an area of 14,510 km^2 or about 5 per cent of such area in the Ferozepur and Bhatinda districts of the Punjab State. Likewise the southern parts of Hissar, Rohtak, Bhiwani and Sirsa districts of Haryana account for an area of 12,840 km^2 or 4 per cent of the total desert area.

The Indian hot desert has 19 million people as per 1971 Census. Of this population, 15 per cent live in Gujarat, 14 per cent in the Punjab and 10 per cent in Haryana. Most of them are cultivators and agricultural labourers. About 28 per cent are engaged in other occupations, such as the salt industry and stone-quarrying (Malhotra *et al.*, 1972).

In Gujarat, three kinds of deserts are identified. They are salt desert, clay desert and stone desert whereas in the Punjab and Haryana, only the sandy desert is commoner. Each of these deserts has certain features unique of its own in respect of geomorphology, soil and land use in the respective States. These are described below:

GUJARAT

Geomorphology

Hills of moderate heights, pediments, mud flats, saline flats and sandy plains (Plates **f**, **g**) constitute the dominant landforms. The hills are made of sedimentary rocks of the Jurassic period lapped by the Deccan traps (the Deccan lavas-basalts) and the sediments of the Tertiary period. The sediments were deposited in the shallow basin of the marine environments. This region, according to the observations of Adyalkar (1964) and Wadia (1966), was in the grip of stupendous marine activities during the Jurassic, Upper Cretaceous and Miocene periods. The Jurassics are resting over the Pre-Cambrian basement bordered on the south by the Deccan traps and the Tertiaries, and on the north by the Ranns. They occupy three anticlinal ridges trending east-west, and owing to parallel faulting the whole sequence is repeated. While the northern 160-km range is broken up into 4 islands of Patcham, Karrir, Bela, and Chorar in the Rann, the middle range, which is 165 km long, extends from Lakhapat east-south-eastwards and the southern ridge south of Bhuj, 65 km long, occupies Charwar and Katrol hills. In between Bhopalka and Baradia are the lateritic formations. This is the product of the sub-aerial alteration of the basalts. The Deccan-trap region consists of small hills of basalts and clusters of dykes and sills of low heights throughout the districts of Jamnagar, Rajkot, Surendranagar and

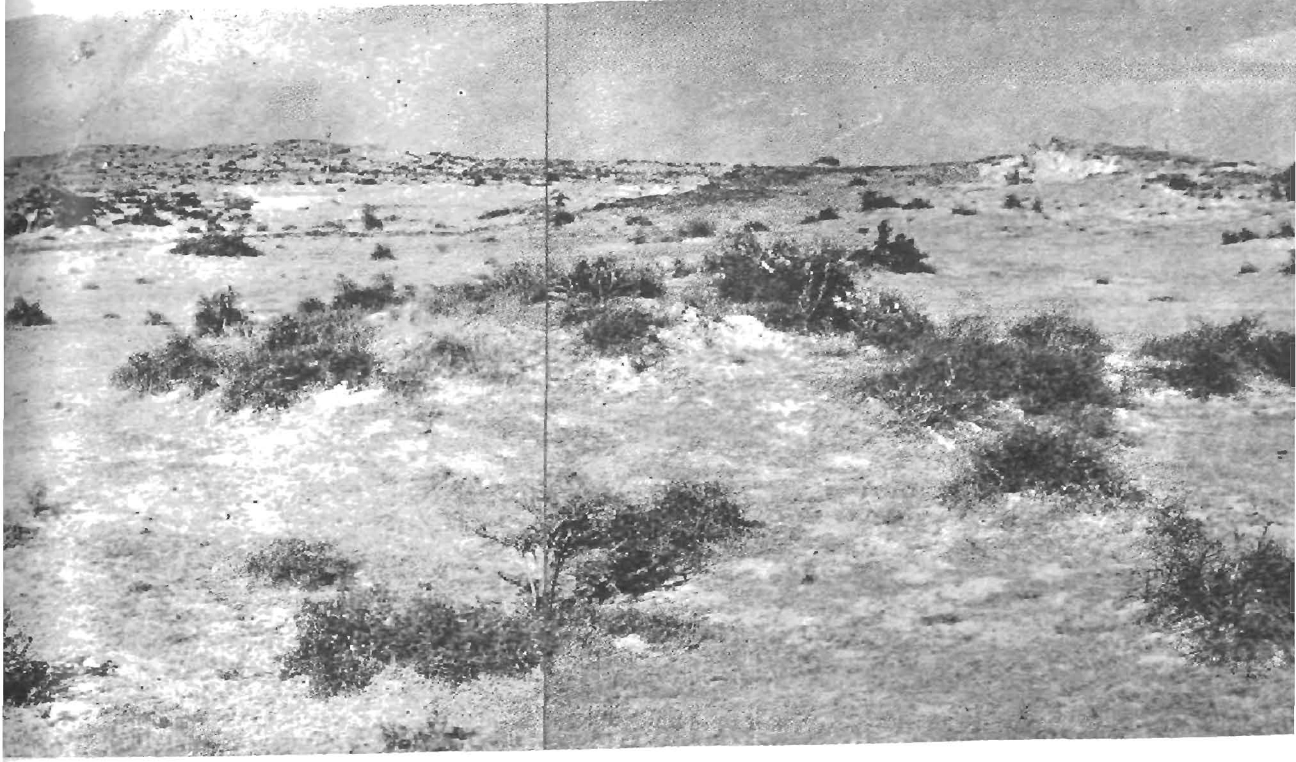

Plate g. Pediments formed along the hills of Bhuj area

Plate h. Desiccated unbroken surface of dark silt incrusted with salt

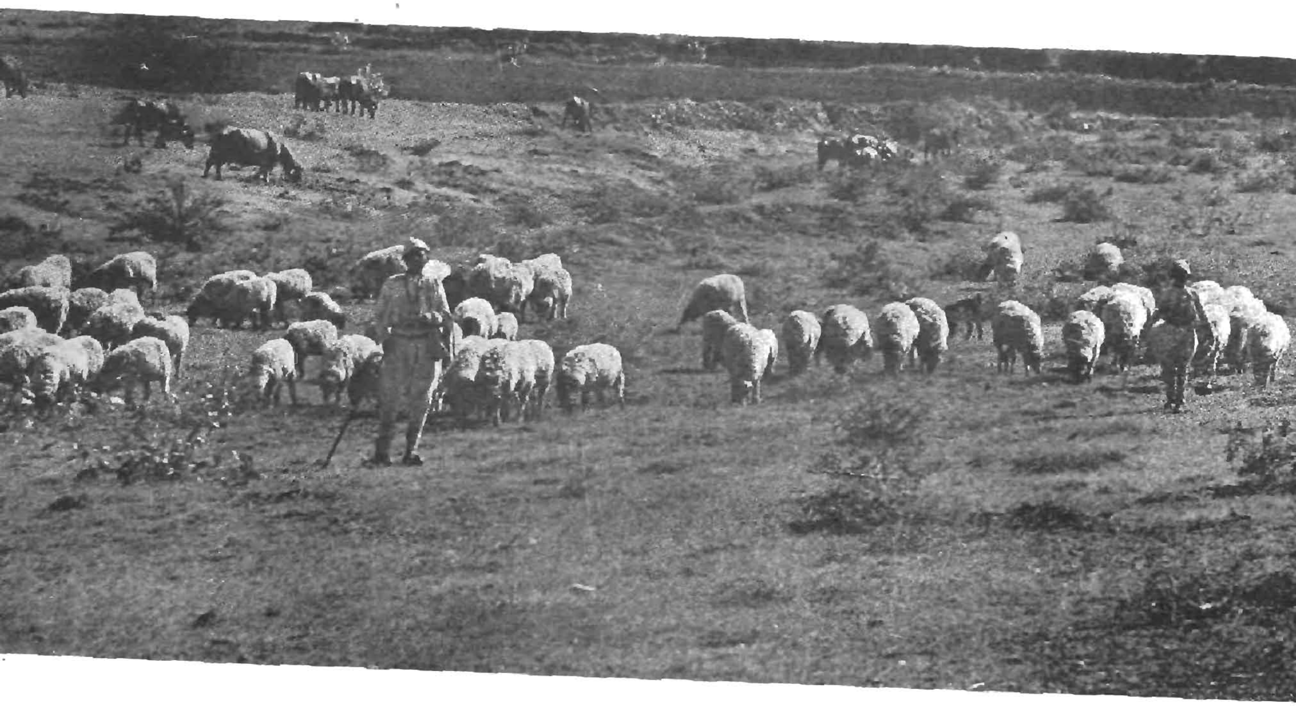

Plate i. Animals graze over almost bare surface

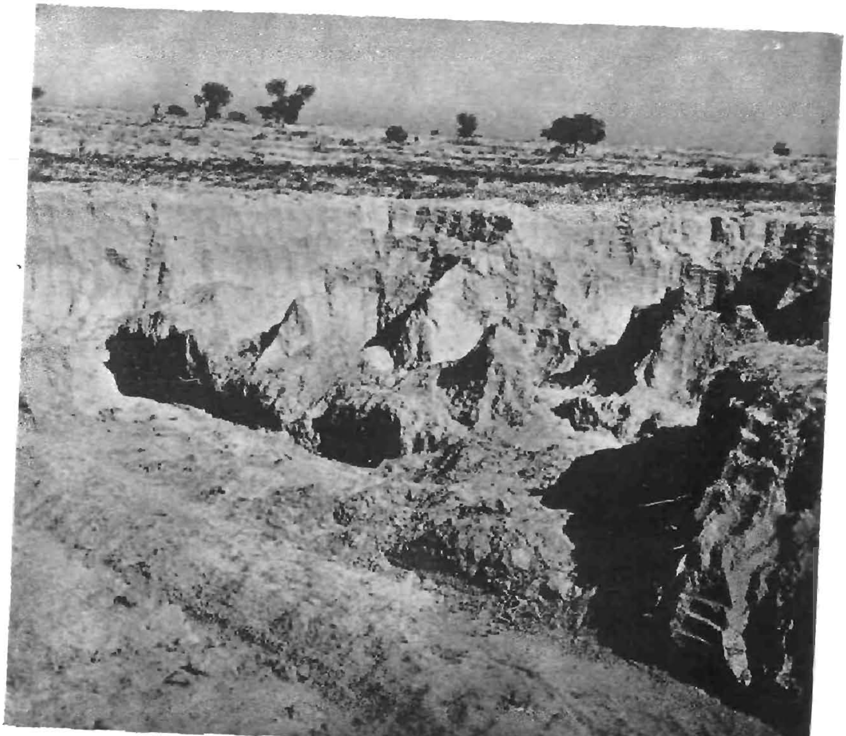

Plate j. Typical soil profile in sandy tract southern part of Kutch.

The pediments with thin cover of coarse detritus have developed over the above rocks. They are mostly flat, except near the hills where the slopes vary from 3° to 8°. The evidences of desert varnish are also met with.

There is extensive coastal tract stretching from Lakhapat to Okha interspersed with the several creeks. Owing to siltation and uprising of the continental shelves, mud flats have been formed. The tides affect these flats by inundating them almost every day. The mud flats are unstable land surfaces remaining almost wet throughout the year.

The saline flats which are known as the Great Rann of Kutch and the Little Rann of Kutch were once part and parcel of the Arabian Sea. Presently, they have been silted up by sediments of finer texture by the Luni, the Banas, the Saraswati, the Rupen, the Phulka, the Bambhor, the Machhu and several other small streams draining into them. It is a vast desiccated unbroken bare surface of dark silt incrusted with salts (Plate h). They cover about 22 lakhs of hectares.

The sandy plains are mostly found near the dry beds of the ephemeral streams. The sand cover is of limited depth. These plains are not so extensive as those formed in other parts of the desert in the country.

The streams originating from the uplands are very few. They are shorter in length. Water flows only when there is rainfall in the catchment.

Soils

Roy *et al.* (1971) and Kanzaria (1972) have classified the soils of the desert tracts of Gujarat into the following:

(*1*) *Sandy soils*. These soils include loamy sand to sandy loams in the upper horizon, with a considerably high percentage of coarse fractions. The fine material has been leached to lower horizons, as revealed by the accumulation of clay. The exchangeable bases are much less than those in black soils because of the low percentage of clay. The percentage of silica (acid-insoluble) which is as high as 94.6 in the upper horizon is a reflection of coarser material in the soils. The soils are non-calcareous. They are neutral to mildly alkaline and have good drainage.

The soils are sandy and they show a very high permeability (58 cm/hr). The maximum water-holding capacity is about 25 per cent; the field capacity is 12 to 15 per cent; the pore space is 45 per cent and the expansion is 3 per cent.

Roy *et al.* (1971) have described light-textured deep soils in the Banaskantha District. They are calcareous throughout.

(*2*) *Medium black soils*. Being derived from the basaltic trap, the depth of the soils varies from a few centimetres to about 0.6 metre or more and, as such, at some places they are very shallow and can thus be termed even shallow black soils. They are calcareous and residual in character, except in low-lying areas. A layer of murum (decomposed trap) is found at a depth of 0.4 to 0.6 metre. Carbonate concretions are found throughout the depth of the profile. The colour varies from dark grey to light grey.

The soils are clayey though clayey loams are also common. The soil is neutral to alkaline, with calcium carbonate ranging from 3.56 to as high as 22.56 per cent in different horizons of the profile. Calcium is the dominant exchangeable cation, followed by magnesium. Sodium and potassium, although present to some extent on the surface, have a tendency to increase with depth. The contents of silica (acid-insoluble), alumina and iron are fairly constant.

(*3*) *Dark heavy-textured soils*. In depressional areas and also in small pockets, the top soil is a dark heavy clay which is underlain by light-coloured sand or loamy sand. The soil has been formed by the washing of the fine clay particles into the low-lying areas. There is thus a distinct demarcation in the profile between the original sandy soil at the bottom and the dark clay soil on the top. This deposition horizon is variable in thickness from 20 cm to at least a metre or so. Being situated in the low-lying position, the soil has developed salinity of varying degrees.

A typical soil profile is described below:

0–20 cm Dark-greyish-brown to very dark-greyish-brown clay; strong angular blocky structure; dry and extremely hard; strong effervescence with HCl.

20–28 cm Greyish-brown to dark-greyish-brown silty clay; prismatic structure breaking into strong angular blocks; dry and extremely hard; strong effervescence with HCl.

28–45 cm Pale-brown to dark-greyish-brown silt; no structure, slightly moist and plastic; strong effervescence with HCl; white crystals of salt present.

45–60 cm Pale-brown to brown loamy sand impregnated with white salt crystals; no structure; somewhat moist.

Where salinity is not high, cultivation is practised.

(4) *Coastal alluvial soils.* Occurring as a narrow strip these soils are formed from a mixture of black clayey material and old marine silt deposits; they are fairly deep sandy clay loams. They are calcareous; both the exchangeable and the total calcium are high; so are iron and alumina. The maximum water-holding capacity is about 35 per cent; the field capacity is 15 per cent; apparent specific gravity is 1.433, the pore space is 47 per cent, expansion is 8 per cent and the downward movement of water is 27 cm/hr.

(5) *Saline soils.* Saline soils occur along the seacoast formed owing to the effect of tidal water. The Bhal tract is the area with a flat topography formed because of the alluvial deposits brought by the rivers flowing into the Little Rann. The area under the Little Rann is 3.5 lakh hectares. The area under the Great Rann is 15.7 lakh of hectares. With the turning of tides, when water comes to a standstill for a short while, the silt contained in tide water is deposited as a thin film over a large area. This process, continued over the years, has created saline conditions in the soil of the Bhal tract. The salt content varies from 1.5 to as high as 5.7 per cent. Calcium is the dominant cation in the clay complex. The saturation of sodium in the clay complex has raised the pH to 9 in some layers.

(6) *Shallow skeletal or lithosolic soils.* The skeletal and lithosolic soils derived from ferruginous sandstones, limestones, shales and basalt are found on the pediment. These are reddish-brown shallow soils of light texture. In pockets, however, the soil is of sufficient thickness to permit cultivation.

(7) *Deep gravelly soils in the foothills.* These soils are sandy loams but are mixed with gravel which distinguishes them from the light soils in the region. The water-retention capacity is low. The soils are susceptible to water erosion.

Land Use

Cultivated lands are limited in extent. As reported by Malhotra *et al.* (1972), the land classified under non-agricultural uses and the barren and un-culturable waste occupy nearly 58 per cent and the net sown area is about 28 per cent of the arid region of the State. The culturable waste takes the share of the rest. The position of pasture and grazing lands is not encouraging. Animals graze almost on bare surface (Plate i). The double-cropped area is negligible, except along the valleys where groundwater has been tapped and used for irrigation. The major crops grown, with poor yields in this tract, are *bajra*, *jowar*, groundnut and cotton. Wherever water is available, wheat and sugarcane are grown.

PUNJAB AND HARYANA

Geomorphology

The areas affected by desertification in the States of Punjab and Haryana are sandy and consist of sand-dunes of different types and low barren hills. Along the streams, marginal flood plains have developed. Most of the dunes are of low heights, except in individual cases where the heights may go up to 20 metres. The dunes are almost barren. The *barchan* dunes of low height are being formed on the flat alluvial plain. The residual hills of the Aravalli Range are noticed at places in the Haryana State. Saline lands are also found in scattered patches.

The streams remain almost dry, except in the rainy season. Despite their originating from the Himalayas, they die out in the desert sands.

Soil

The soils of this region have been studied and described by several workers, e.g. Roy *et al.* (1970), Sidhu *et al.* (1972) and Sekhon *et al.* (1972). Mostly, sierozem and desert soils are found to occur.

(*1*) *Sierozem soils.* According to Sidhu *et al.* (1972) these soils are found in parts of Rohtak, Hissar, Sirsa, Bhiwani and Mehendragarh districts receiving 300 to 500 mm of rainfall in the year. The pH ranges from 8.0–8.6, $CaCO_3$ is 1.84%, organic matter is 0.50%, available nitrogen is 0.04%, the available N is 88 kg/ha and P_2O_5 is 20 kg/ha. Salinity and alkalinity are serious problems, particularly in the irrigated area. Soils are calcareous and usually have a massive *kankar* layer at depths of 0.75 to 1.25 m. These soils are deficient in nitrogen, phosphorus and potash. Gram, wheat, *bajra*, *jowar*, barley cotton, rape and mustard are the main crops of this zone.

(*2*) *Desert soils.* The areas receiving less than 300 mm of annual rainfall in the southern parts of Sirsa, Hissar, Rohtak and Mahendragarh have these soils. According to Sidhu *et al.* (1972), they are deficient in nitrogen, phosphorus and potash. The available N and P_2O_5 are 84 kg/ha and 18 kg/ha respectively. The exchangeable copper and zinc are deficient. Iron is sufficient in the south-western part. In the gently to moderately sloping topography formed on the wind-deposited sand-dunes, the soils that are predominantly sandy are very deep, pale-brown to light-yellowish-brown loamy sand or fine sand. The subsoil is calcareous. Along the dune slopes (less than 3 per cent) and at the toe of the dunes, the soils which are generally sandy loams are very deep and well-drained. The soils are calcareous (Plate **j**).

Land Use

According to Malhotra *et al.* (1972), the net sown areas are about 85 per cent in the arid tracts of both the States. The double-cropped areas are nearly 24 per cent in Haryana and 21 per cent in the Punjab. Owing to increased irrigation and power facilities, additional areas are brought under double and triple crops. Cotton is the primary crop in the western part and gram in the eastern part. During *kharif*, *bajra* is the principal crop. Wheat and sugarcane are grown where irrigation facilities are available (Plate **k**).

Conclusion

The process of desertification being the same, the desert conditions in terms of geomorphology, soil and land use should have been the same in these States. But to a certain extent, they are different. The Gujarat part is mostly rocky and saline, with a shallow black soil cover, whereas the Punjab and Haryana parts are sandy, with dunes of thick deposits of sand. From the land-use point of view, the gap is quite large. This gap can be narrowed down if water for irrigation and desalinization is made available in the desert parts of Gujarat also. Where power and tube-wells have been provided, the change in land use is towards the positive side and desertification is gradually reversed. Similarly, the different resource parameters are being stabilized in the Punjab and Haryana. Thus there is a move to make the desert lands also more productive and prosperous by harnessing the various resources available in the States.

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14

THE RAJASTHAN CANAL PROJECT

A. S. KAPOOR AND B. S. RAJVANSHI

THE Rajasthan Canal, being constructed in the north-western part of Rajasthan, covers part of the Thar Desert and the construction of this canal in such an inhospitable and hazardous area is a challenging task. The Project comprises two stages of construction, the first stage covering 204 km of the Rajasthan Feeder, 189 km of the Rajasthan Main Canal and a service area of 0.54 million hectares is nearing completion, while a start has been made in the Stage II. Meanwhile, efforts to colonize the area have started bearing fruit, and the improved methods of agriculture and irrigation are being introduced. The Command Area Development and on-farm development works for a service area 0.20 million hectares have been taken up. For them, a separate Project, costing 1,390 million rupees, was prepared and furnished to the World Bank. The results of the concerted multi-pronged efforts have been found to be self-rewarding. An effort has been made in this article to describe the area, its hazards, the methods of execution, the progress achieved, the financial achievements and the targets.

History records that a river, the 'Saraswati', flowed on the extreme eastern side of the today's Punjab to join the sea near the 'Rann of Kutch'. Historic archaeological finds in 'Mohenjo-Daro' in Pakistan and 'Kalibangan' on the Indian side reveal the existence of a sophisticated civilization that must have prospered in the area. The presence of the 'Saraswati' is further evidenced by some other old maps which show a river joining the sea in-between the Indus and the Yamuna. According to historians, the oft-mentioned Rajput empires could have only existed if there were extensive afforestation and prosperity. The River 'Saraswati' must have been their main source of prosperity. With the passage of time, the afforestation vanished and along with it the river became extinct and in an estimated period of about 5,000 years, the panorama changed from a land of plenty to barrenness. High-velocity sand-laden winds emanating from the 'Rann', the extreme heat coupled with coldness and the wind action carved out the desert through mechanical disintegration of the works. The high-velocity sand-laden winds still menace the area when they are found to reach a velocity up to 150 km per hour. Today, water is scarce all around and as far as the eye can see, the area is rippled with huge sand-dunes and the gleaming surface of sand.

The project area of the Rajasthan canal

The Rajasthan Canal was born with delivery point at Harike to transport 9,856 million cum (8 MAF) of the Ravi-Beas waters through Punjab and Haryana for a distance of 204 km to enter Rajasthan at a point 12 km north of the Hanumangarh Town in Rajasthan. The Rajasthan Canal aims at ushering in a new era into this land. It will convert this barren land into a granary humming with agricultural activity, resulting in development providing for immense job potentialities. It will also enable the State to colonize the area on modern lines and also settle the border area with sturdy peasants. The Harike Headworks was constructed in 1951-58. To fulfil the aims of the optimum utilization of available water by cutting down the transit, seepage or absorption losses, the project was reframed to incorporate into it the latest technology. The aim of the Project has always been to resort to extensive rather than intensive system of irrigated agriculture. (Plates **l**, **m**.)

The Rajasthan Canal after travelling through the Punjab and Haryana States has to pass through Sriganganagar, Bikaner and Jaisalmer districts of Rajasthan. In its initial reaches, it crosses the Bhakra command areas or passes adjacent to the areas covered by the Gang Canal. It enters the heart of the desert near about its 128th km, where not only the water for construction is hard to find but even drinking-water is scarce. The problem becomes more acute on entering areas of the Stage II where still larger dunes have to be traversed. The area is so desolate and without any means of communication that the construction materials and men to do the work are difficult to find. The canal system runs through vast sandy plains and dunes. They consist of very deep calcareous and wind-blown sand to loamy fine sand. The sandy plains are hummocky or slightly undulating, occasionally gently sloping. The infiltration rate and subsoil permeability are rapid and the moisture capacity is low. The major problems of irrigation development of the soils are the wind-erosion hazard and drought. The ground water-table is 50–80 metres deep.

The main source of livelihood of the people in this area is animal husbandry, supported by erratic agriculture. The agricultural community is miserably poor, for the crops depend on the rainfall which is scanty, ill-distributed and erratic. Crops comprise only about 1% of the gross area. *Bajra*, *jowar*, *moong* and *moth* are grown when rains come, but the yields are extremely poor, only 0.3 to 0.5 quintal per hectare. The other means, viz. animal husbandry enables some trade in *ghee* (clarified butter), wool and hides. Sheep, goats and camels are found in plenty and form the main animal wealth. This wealth too, becomes precarious owing to the frequent failures of rains. Every year, the disappearance of grass and water claims a heavy toll of the animals when they are compelled to move towards wet regions. The camel is still the ship of the desert to traverse the terrain.

Mineral resources lie hidden and unexplored. It is only lately that some search for oil has been started in this desert near about Jaisalmer but, by and large, the area has yet to be opened up for full exploitation of its lignite and gypsum which are available in abundance.

Physical targets and the means of construction

For construction, the Project has been divided into two stages, the Stage I and the Stage II, with the following constituents:

STAGE I

Stage I includes the total length of the Rajasthan Feeder, i.e. 204 km and of the Rajasthan Main Canal, i.e. 189 km, with the gross service area of nearly 0.95 million hectares, of which the cultivable commanded area is 0.54 million hectares. The following are the main branches with their off-take points:

Name of the branch	Off-take point on the Rajasthan Main Canal
(a) Rawatsar Branch	Km 0
(b) Nourangdesar Branch	Km 0
(c) Suratgarh Branch	Km 20
(d) Anupgarh Branch	Km 74
(e) Loonkaransar-Bikaner Lift Canal	Km 74
(f) Pugal Branch	Km 189

STAGE II

The Stage II includes the Rajasthan Main Canal from its 189th km to the tail (445 km). The gross service area is nearly 1.10 m ha, whereas the cultivable commanded area is 0.76 m ha. The main branches with their off-take points are shown below:

Name of branch			Off-take point on the R.M.C.
Flow	(a)	Dattor Branch	Km 215
	(b)	Birsalpur Branch	Km 232
	(c)	Charanwali Branch	Km 288
	(d)	Digha Branch	Km 445
	(e)	Lilwa Branch	Km 445
Lift	(a)	System I (Gajner)	Km 228.6
	(b)	System II (Kolayat)	Km 229
	(c)	System III (Phalodi)	Km 351
	(d)	System IV (Pokaran)	Km 366.8
	(e)	System V (Nohar-Sahwa)	Km 0.0

The earlier proposal was to construct the main canal lined with burnt clay tiles, whereas the distribution system was to be left unlined, whereby intensity of irrigation could be kept only at 78%. Subsequently, however, to reduce absorption losses and to make the maximum consumptive use of water, a decision was taken in 1967 to line the branches, distributaries and the minors also, thus generating an intensity of 110% for irrigation of *kharif* (April-September) 47% and *rabi* (October-March) 63%. The earth work to form the embankments of the canals has either been done with the earth-moving machines available with the Project or with manual or donkey labour or both. While the canal work proceeded along in the earlier reaches, a position was soon reached when the cutting of large dunes became essential. It was in 1964 that the camel-cart was used in the Project and the cart has proved to be of great help in carrying out the earthwork at economical rates. Since then, the unimitable camel-carts have been doing most of the earthwork.

The inner sides of the canal embankments are made of earth compacted with sheep-footed rollers after laying moistened earth to the required dry bulk densities and cut to the right shape to form the base for lining to be laid over it as an impervious layer to guard against the seepage and absorption losses. Various types of lining to be adopted were tried, but the most suitable and economical method was found to line the canal with burnt-clay tiles of 30 × 15 × 5 cm size by laying them in two layers, sandwiching between them a thick layer of cement plaster (about 16 mm thick) as the impermeable film.

A good quantity of water is necessary for construction work, e.g. the compaction of earthwork, the manufacturing of burnt-clay tiles, the lining and the curing of the lining so done. As long as we were near the commanded areas of either the Ganga Canal or the Bhakra canals, the water could be obtained from the nearby contact points and transported to the site of works through the pipelines by pumping. Such pipelines were laid along the main canal, wherefrom smaller connections were taken to the kiln sites. But as we proceeded away from such areas, the arrangements for water for construction became more and more difficult. To cope with the problem, a small channel in the bed of the main canal was also made to supplement the pipe supplies till we reached the end of Stage I. By that time, it was felt that for the Stage II areas, which were still farther from the water sources, it was necessary to construct a dependable water-supply channel and, therefore, it was planned to construct such a channel with a capacity of 13 m^3 per sec. (450 cusecs), taking off at km 189 and running parallel to the alignment of the Rajasthan Main Canal. This water-supply channel is to cater for the needs of construction as well as those of drinking water for the labour and staff engaged in the area.

The work on the project in Rajasthan was taken up in 1958, having been inaugurated by the late Shri Govind Vallabh Pant, Union Minister for Home Affairs, in Government of India. In the upper areas, it was seen that clayey soils could be found for manufacturing burnt-clay tiles, but farther in the areas, even the clayey soils had become scarce. The manufacturing of tiles is being done under the Project by handmoulding and by firing them in the trench-type kilns at a temperature range of nearly 760-860°C. The tiles have to withstand a tensile strength of 8.5 kg per sq cm and the flexural strength of 15 kg per sq cm.

In consonance with the earlier decision to construct the branches without lining, the work on the branches and the system was taken up on a good scale and the uppermost branches, viz. Naurangdesar and Rawatsar branches, along with their distribution system, were commissioned by releasing water into them on 11 October 1961. Likewise, the Suratgarh Branch was also commissioned in November 1962, with the part completion of the distribution system. Similarly, the Anupgarh Branch was commissioned when water was released into it in June 1967 for the first time when its distribution system was partly completed. The branches and their systems upstream of km 74, earlier left unlined are now being lined with burnt-clay tiles of the same size and specifications as those of the main canal. The construction on Loonkaransar-Bikaner Lift Canal was inaugurated on 5 August 1968 by the Hon'ble Shri Mohanlal Sukhadia, the then Chief Minister of Rajasthan, with the simultaneous taking up of the work on the four gigantic pumping-stations. This lined lift channel, too, was completed in 1975. The distribution system is being lined and has been completed by now to the extent of 70%.

The development project of the command area is to provide amenities, such as habitation and housing, communications, demonstration farms, industries, forests, power, education, health and co-operation. To consider and plan the overall development in the command area, the State Government has established a development authority for the command area. The authority has been in position during the last two years and it has taken up, besides other development works, land-levelling and the lining of water-courses for 0.20 million hectares in the project area, for which a loan from the World Bank has been secured. The specifications for the lining of water-courses have been evolved and they provide for a base layer of cement mortar, followed by the sandwich plaster, covered by a layer of 30 × 15 × 5 cm-sized burnt-clay tiles. To carry out lining on the channels which are in operation is a difficult task in itself, as the construction schedule has to be so devised that it does not upset the irrigation programme or the production. For this purpose, the lining of the existing and flowing channels is being done even by diverting supplies by making a bypass channel of the required shape and size.

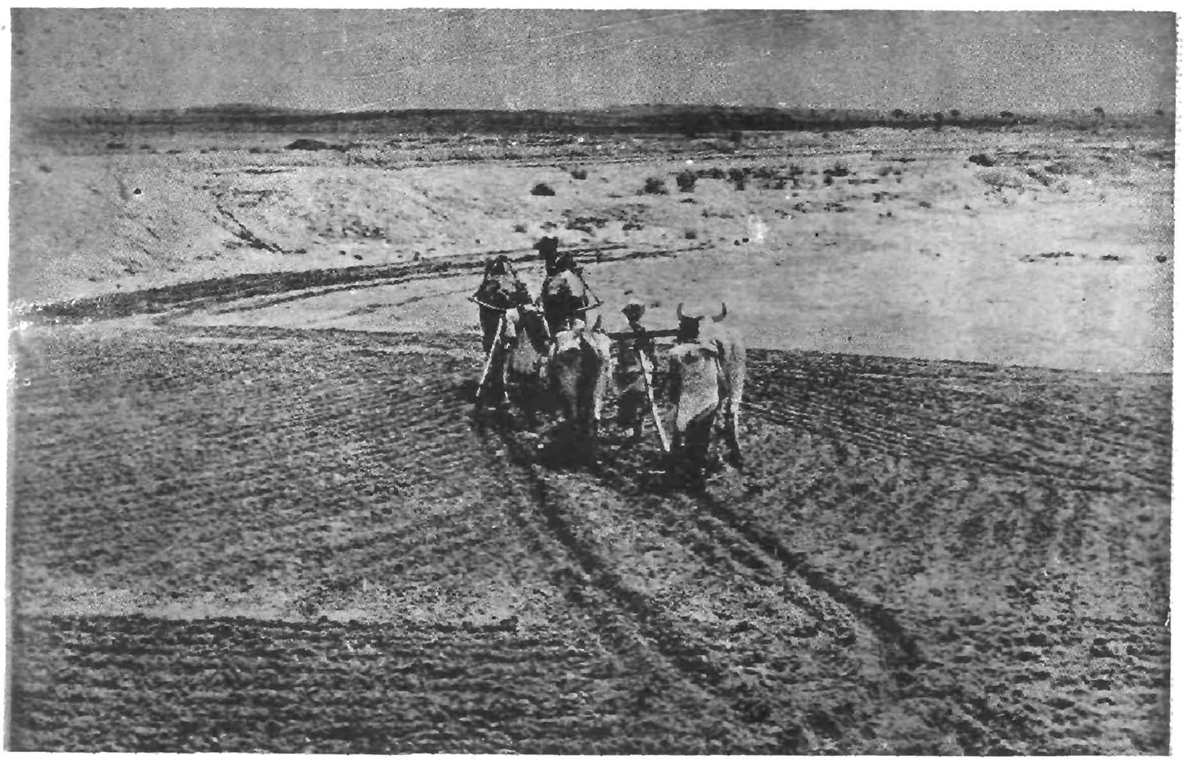
Command area development

The cost of carrying out the development works of the area for 0.20 m.ha in the Stage I is estimated at 13,90 million rupees and a World Bank credit of 680 million has been secured for it, with the participation by the Government of India, the Government of Rajasthan and institutions such as the Agriculture Refinance Corporation and Commercial Banks. The Project is to use labour-intensive methods, wherever feasible. Since the work of lining the water-courses and land-shaping is done at the cost of the farmers through the loans granted by the banks and the Agriculture Refinance Corporation, the farmers will have a considerable debt burden. The financial position was, therefore, examined and the investments on and the returns from the farms of 6.32 hectares on sandy or on 'Tal' soils were examined in some detail over a period of 20 years. After making appropriate deductions for hired labour, farm inputs (e.g. fertilizers, seed and plant protection) and water charges and allow-

Plate k. Wheat grown in *rabi* season under irrigation

Plate l. For man, animal and plant, the Rajasthan canal brings in hopes of survival and prosperity

Plate m. The canal water harnessed for agriculture. Water-less wastelands are being turned into agricultural fields



ing a family consumption of Rs 5,000 per year, the cash position of the project farmers was shown to be satisfactory. The farmers would be able to meet their debt obligations because of land purchase up to Rs 20,000 and on-farm development loans up to Rs 15,000. The incremental net value of production in the 11th year would be 250 million rupees, and on full development in the 21st year, it would be 350 million. The economic rate of return works out at 25% and its implementation would take six years.

The cost of the on-farm development works (as in 1976) for the remaining area of 0.34 million hectares of Stage I (including 5,8000 ha on the Loonkaransar-Bikaner Lift Canal) on the above analogy works out at 543.20 million rupees, whereas for the Stage-II area of 0.76 m.ha, it is estimated at 1,185 million rupees. This amount would be needed, as and when it is sought, to develop the command areas.

The up-to-date progress

(a) *The physical progress on the project works.* The first stage of the project is now nearing completion. The position in respect of the main constituents is given below. Water is running in all these branches (Table I).

Preliminary works for the Stage II were started in 1970. The first and foremost work was of water-supply channels. It has since been completed to a length of 110 km downstream of km 189 of the Rajasthan Main Canal and water was released into it in November 1975. This step has eventually facilitated the commencement of earthwork, and the manufacturing of burnt-clay tiles in about 30 kilns is in operation. The making of earthen embankment from km 189 to km 260 has been in progress along with the lining work of the 20 km of the main canal during 1976-77.

In respect of the development of the command areas by September 1976 the survey and planning of the on-farm development works had been completed in 536 blocks (*chaks*) covering more than 80,000 hectares. The construction of the lined water-courses had been taken up in 191 *chaks* and by March 1977, the on-farm development works would be carried out in about 30,000 hectares.

Irrigation

Ever since 1961, the irrigation picked up and the steps taken in 1958 started bearing fruit, as shown in the Table below.

Year	Area irrigated (in hectares)
1961-62	1,445
1962-63	1,404
1963-64	6,407
1964-65	17,808
1965-66	26,950
1966-67	42,268
1967-68	81,534
1968-69	1,00,036
1969-70	1,42,169

(*Contd.*)

	Name of the unit	*Length*	*State of work*
i.	The Rajasthan Feeder	204 km	Completed
ii.	The Rajasthan Main Canal	189 km	Completed
iii.	The Naurangdesar Branch System		The complete lining of branches and laterals is being done
iv.	Rawatsar Branch System		,,
v.	The Suratgarh Shakha System		,,
vi.	The Anupgarh Shakha System		,,
vii.	The Loonkaransar- Bikaner Lift canal		The distribution system duly lined is 70% complete and will be fully completed by 1977-78
viii.	The Pugal Branch		,,

1970-71	1,74,000
1971-72	1,85,475
1972-73	2,01,281
1973-74	2,25,055
1974-75	2,50,000
1975-76	2,88,0[illegible]0

Water was released below km 74 of the main canal in June 1974 and below km 128 in the Pugal Branch in June 1975. Areas coming under command from km 74 to km 128 started receiving irrigation water from the *kharif* (April-September) crop 1974, whereas those between km 128 and 189 and the Pugal Branch did so from *kharif* 1975. All the channels below km 74 are being constructed complete with lining in the very first instance, whereby the laterals have taken a longer time in completion than unlined ones. Efforts have, however, been to supply irrigation up to whatever points the laterals were ready and in this manner the additional venues for irrigation were created in 6,5000 ha (CCA). The area opened for irrigation increased to 0.44 m.ha in Stage I. The actual irrigation done during 1975-76 was 0.29 m.ha (7,20,000 acres).

Areas irrigated

Gross area	2 m.ha
Culturable area	1.30 m.ha
Area to be irrigated annually	1.26 m.ha
Area irrigated in 1975-76	0.29 m.ha

Financial

Out of the total required outlay of 4060 million rupees, as assessed in December 1976, the expenditure already incurred stood at 1,500 million rupees at the end of March 1976, including 130 millions on the Stage II as well as on the lining of the distribution system upstream of km 74 of the Rajasthan Main Canal. During the current year 1976-77, another 235 million rupees was spent, 83.20 millions on the lining of laterals above km 74, nearly 96.8 millions on Stage I and 55 millions on Stage II. The fiscal position emerges to be as under at the end of the year (1976-77).

FIGURES OF COSTS

1957 estimates:	610 million rupees
1963 estimates:	1,400 million rupees
1970 estimates:	2,170 million rupees
1975 estimates:	3,310 million rupees
1976 estimates:	4,060 million rupees
Expenditure incurred up to March 1976	1,500 million rupees

	Stage I	Stage II	Total
	Rupees in millions		
Estimated cost (1976)	1,760	2,300	4,060
Expenditure till March 1977	1,550	185	1,735
Balance required	210	2,115	2,330

Employment potential

As already explained, the project has immense employment potential and can employ up to a hundred thousand skilled and unskilled labourers, but the area is famine-stricken, climatically hazardous, devoid of means of communication and without habitation, and very desolate. It is only in the famine years that the labour strength has been reaching 60,000. In normal years, it does not exceed 30,000. The project makes the dwelling arrangements for the labour and supplied drinking-water free of charges. The tools and plants (T&P) required for doing the work are also supplied free. Even though the project has recently replenished its earth-moving fleet, there is a vast scope for employment. The project, in collaboration with the Food and Agricultural Organization (FAO) under the World Food Programme also supplied wheat, *ghee* (clarified butter), soybean and milk powder (soybean and milk powder are not being supplied now) at concessional rates (about one-half of the market rates) to bona-fide project workers drawing up to Rs 250 per month.

The proper method for the distribution or sale has been evolved and the agency to plan and co-ordinate the sale and its proceeds is in position. The representatives of the World Food Programme fre-

Table 1. The Rajasthan Canal Project—The Statement of Progress

Stage	Name of work	Unit	Estimated quantity	Completed up to 31 March 1976	Target for 1976-77	Completed up to November 1976
I.	Up to km 74 of the RMC (CAD) including its distribution system					
(a)	Earthwork	Lac cu m	382 05	359·21	2 00	4·11
(b)	Lining	km	1,849·88	847 95	220 00	105 02
(c)	Water-courses (OFD works)	km	5,800 00	25 00	350·00	117·00
	Beyond km 74, up to km 189 of the RMC, including its distribution system					
(a)	Earthwork	Lac cu m	248 27	199 40	36 01	23 15
(b)	Lining	km	714 02	251·59	214·72	82 81
	Lift canal (Bikaner-Loonkaransar Lift), including its distribution system	Lac cu m	214.68	207.39	5.45	1.77
(b)	Lining	km	337 64	267·56	52 08	14 85
(c)	Water-courses	km	1,524·00	220·98	240 00	150 20
II.	Beyond km 189, including its distribution system					
(a)	Earthwork	Lac cu m	846·17	176 78	52·35	32 90
(b)	Lining	km	256 00	—	11·25	—

quently visit the Project sites and have expressed their satisfaction with the arrangements.

Bottlenecks

Physical. As explained above, the area is desolate and devoid of all means of communication and is bereft of all civic amenities. It is climatically hazardous. The labourers and other workers feel reluctant to go to the site at the outset. The area is sandy and can be reached either by four-wheeled vehicles or by using the indomitable camel. Thus there is a necessity of laying a proper network of communications which will also ease the transportation problem. Even though the project has constructed a road by the side of the main canal, it cannot help to feed the distribution systems to any significant extent. There are no schools, hospitals or dispensaries or markets to enable normal habitation. Even the postal facilities are scarce. These hard conditions deserve to be recognized and a suitable formula has to be evolved to ameliorate them.

As we now enter the heart of the desert, the rail-heads get farther and farther and this increases the period and cost of delivering the construction material and men at the site of the work. The work of laying adequate rail-links needs to be initiated.

Financial. The pace of work under the project has been restricted mainly because of the paucity of funds for the gigantic task. Rajasthan is a backward State and has to cover a lot of leeway in bringing its people on a par with those of other States and thus cannot afford to ignore its overall development. It cannot afford to finance adequately a project in the north-western part from its own resources. It need not be reiterated that the project will bring immeasurable benefits to the State and there is a need to accelerate its pace and complete it as soon as possible. With the tempo already created, the available manpower and the technical skill, it is possible to complete this gigantic task soon, provided adequate funds are made available. Moreover, the Pong Dam on the Beas is complete, and the availability of supplies for the annual irrigation for the development of 1.28 m hectares is assured.

Conclusion

The project is capable of increasing food production, creating immense job opportunities and transforming the desert into a granary, raising the standard of living of the down-trodden and nomadic people of the area. When the source of perennial supplies to the canal is assured and, with the improved methods of agriculture, the virgin area lying uncultivated for centuries will be developed and the march of the desert will also be arrested. The revised cropping pattern for the Rajasthan Canal Project area is given in Table 2.

Table 2. The revised cropping pattern of the Rajasthan Canal Project

(Perennial irrigation)		
(I) *Kharif*		(Intensity 47%)
1	Vegetables	1·0
2	Cotton	16·5
3	Groundnut	5·0
4	Pulses	7·5
5	Fodder crops	4 5
6	*Bajra*	12·5
(II) *Rabi*		(Intensity 63%)
1	Wheat	30
2	Mustard	10
3	Gram	20
4	Sugar-beet	2
5	*Berseem* (fodder)	1
	Total :	63

The paramount need is to complete the project at the earliest opportunity. With the available manpower and technical skill and the tempo already created, it is possible to complete the project provided adequate funds are made available. Even at the end of the financial year 1976–77, the balance requirement works out at 2,330 million rupees. Considering the fillip that the development of the command area would induce in the production and economy of the farmer, the remaining areas need also to be developed. For the proper opening up of the area, a network of roads and railway lines should also be laid to create the proper infrastructure. For providing the personnel deployed on the Project with proper facilities, the base colonies need to be developed and quick means to reach the sites of work made available. There is no doubt that the project will boost the economy of the State and its people to a great extent.

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SALINE WATERS—THEIR POTENTIALITY AS A SOURCE OF IRRIGATION

R. P. DHIR

THE occurrence of saline and highly saline waters is a common feature of the arid and semi-arid regions of the country. In the arid part of Rajasthan, nearly 84% of the area has ground-water of over 2.2 mmhos EC. The adjoining semi-arid area of the State as also of the neighbouring States of Gujarat, Punjab, Haryana and Uttar Pradesh are also beset with this problem, albeit, to a smaller degree. The semi-arid areas of peninsular India have high residual carbonate in the majority of waters. Only in small parts of the regions concerned has it been possible to divert good-quality surface waters from outside the area and the major part of ground-waters remain the sole source to supplement low and erratic rainfall for crop production. In western Rajasthan alone, there are over 0.30 million ha under irrigation from ground-water and an equally large potential still exists. Realizing the importance of ground-water, the Indian Council of Agricultural Research has recently launched an all-India co-ordinated project on the use of saline waters.

The ground-waters, such as those occurring in the area are considered unfit according to most of the internationally accepted norms and in our own country also their use is looked upon with great scepticism. An attempt has been made in this paper to give a brief account of the valuable work done in the country on different aspects of the use of saline water. In one of the sections, an account is given also of a medium-term investigation carried out at a number of sites irrigated with highly saline water on a variety of soil textures. The last section constitutes a resume dealing with the usage potentialities of the saline waters in an arid environment.

IRRIGATION QUALITY CHARACTERISTICS OF GROUND-WATERS

The chemical analysis of ground-waters has been an essential part of many studies aimed at surveying and assessing this important resource. As a result of decades of the activities of different organizations in the field, valuable information has been obtained in respect of arid and semi-arid regions in different States and a brief account of the work follows.

Rajasthan. Rajasthan is one of the few well-investigated States in the country. Thanks to the efforts of the State and Central Ground-Water Boards, the Geological Survey of India, the Central Arid Zone Research Institute, the State Public Health, the Agriculture Department, the Defence Science Organization and the Udaipur University, a fairly good picture is now available. The findings of most of these bodies have earlier been summarized by Paliwal (1972). These, updated with major efforts that have been made since then in western Rajathan, are summarized in Table 1.

It may be seen that saline to highly saline waters, i.e. those above 2.25 mmhos E.C. constitute over 60%, with a small inter-district variation. The results obtained by Dasgupta (1975), showing the geographical area occupied by different

Table 1. The distribution of water samples in different salinity ranges in western Rajasthan

S. No.	Name of district	The number of water samples	Percentage of samples falling in E.C. range (in mmhos)						
			Below 0 25	0·25-0·75	0 75-2·25	2·25-5·00	5-10	10-15	above 15
1.	Barmer	322	5·9	4·0	10·6	31·4	26·7	14·6	6·8
2.	Bikaner	137	—	1·5	27·0	36·5	21 2	10·2	3·6
3.	Churu	244	—	3·3	16·4	29·5	28·7	14·7	7·4
4.	Jaisalmer	295	0 3	18·6	36·6	19 7	20·3	3 8	0·7
5.	Jalore	505	—	9 5	27·7	29·9	19·8	10·3	2·8
6.	Jodhpur	357	—	7·8	37·6	26 6	16·0	7·8	4·2
7.	Nagaur	459	0.2	7 6	35·7	28·2	21·7	3·8	3·1
8.	Pali	498	—	12·3	33·5	20·1	17·1	9.0	8.0
	Total	2,817	0·8	8·9	29·2	26·8	20·8	8·9	4·6

Table 2. The district-wise distribution of area occupied by waters of different salinity ranges (Dasgupta, 1975)

Districts	Area of districts in sq. km	Approximate percentage of the district having total dissolved salts		
		Below 2·2 mmhos	2·2-3·6 mmhos	Above 3 6 mmhos
Barmer	29,031	10	22	68
Bikaner	27,102	5	17	78
Churu	16,261	9	9	82
Jaisalmer	38,475	9	20	71
Jalore	10,428	20	15	65
Jodhpur	22,213	30	15	55
Nagaur	17,292	20	13	67
Pali	11,808	25	19	56

salinity ground-waters based on the iso-salinity contour maps (Table 2) also present a similar picture.

The ionic composition of ground-waters shows considerable variation. The results of most of the studies show that in low-salinity ranges, the waters are of the carbonate-chloride type and at 2. 5 mmhos EC these waters become chloride-bicarbonate type. With a further increase in salinity, the waters are invariably of the chloride-sulphate type. The percentage of sodium also continuously increases with salinity. These trends are excellently brought out in a compilation study, results of which are presented in Table 3. It may also be seen that for Rajasthan as a whole, magnesium dominates over calcium in 73% of the water samples. There is an appreciable variation also in anion composition. For example, in highly saline waters in an area of 5,000 sq.km in Pali, the sulphate content ranged from 4. 8 to 45. 7% of the total anions. As regards carbonates plus bicarbonate, they rarely constitute more than 15% of the total anions, but in the salinity ranges below 2. 2 mmhos, they occur in a large range of 24 to 78%.

The sodium-adsorption ratio (SAR) is an important criterion and defines the sodicity of waters. Table 4 presents the distribution of waters in different SAR ranges.

It is evident that in waters above 2. 25 mmhos EC, by far the majority of the samples have SAR values above 10. At higher salinity, the values, in fact, are mostly above 26. Waters below 2. 25 mmhos E.C. have SAR values generally below 10, but knowing that these waters often contain residual carbonate, these waters also are not free from sodium hazard. Therefore the waters in the arid zone of Rajasthan are characterized not only by salinity but also by high sodium content.

The adjoining semi-arid districts of Rajasthan have also been reported to possess the water-quality problem. Paliwal (personal communication), on the basis of 334 samples collected from the Alwar District, obtained a mean salinity of 2.4 mmhos. In 276 samples from Bharatpur, the mean values were 3.1 mmhos, in 235 samples of Bhilwara, they were 5.5 mmhos and in 702 samples of Jaipur and Sawai Madhopur they were 2.4 mmhos. These observations show that even semi-arid tracts of the State have the problem of ground-water salinity, though it is not so acute as in the arid part.

Boron in irrigation waters can be toxic

Table 3. Ionic composition in relation to electrical conductivity in well waters of Rajasthan (K.V. Paliwal, personal communication)

Ions	The mean percentage composition in different salinity ranges (in mmhos)			
	0-2	2-6	6-10	Above 10
Cations				
Na^+	51·9	70 3	72·2	74 1
K^+	1·5	3·2	2·3	1 6
Ca^{++}	20·4	9 4	8·9	9·2
Mg^{++}	26·2	17·1	16 6	15 1
Anions				
Cl^-	30·2	54·1	67·2	75·3
SO_4^{--}	10·3	15·3	20·4	15·2
$HCO_3^-+CO_3^{--}$	59·3	30·6	12·4	9·5
Number of samples	1,671	1,372	545	344

Table 4. Distribution of waters of western Rajasthan in different sodium-absorption ratio ranges

Salinity group (E.C. in mmhos)	Number of water samples	Percentage distribution in different sodium adsorption ratio ranges				
		0-10	10-18	18-26	26-34	Above 34
Below 0·25	3	66 7	33·3	—	—	—
0·25–0·75	167	93·4	5·4	1·2	—	—
0·75–2·25	607	72·8	21·5	3·6	1·8	0 3
2·25–5 00	659	31·0	39 4	22·3	4·7	2·6
5–10	496	6·6	28 6	31·9	21·2	11·7
10–15	225	2·2	12·5	30·7	33·3	21·3
Above 15	121	3·3	4·1	12·4	22·3	57·9
Total	2,278					

and can severely limit their utility. Though as high as 5 ppm of boron have been found in waters, in by far the majority it ranges from 0.67 to 2 5 ppm (Fig. 1). Mondal (1967) reported for arid districts a range of 0.28 to 7.66 ppm, with a significant positive correlation between E.C. and the boron content. Thus it seems plausible that the majority of waters are unfit for sensitive crops, although they are moderately suitable for semi-tolerant and tolerant crops.

Gujarat. A State-wide survey showed that of the 8,952 samples, samples with E.C. values over 3 mmhos and those between 2 and 3 mmhos constitute nearly 15% (Shah and Bapat, 1972). Talati (1969), while working in the alluvial plains of Gujarat, showed that in some pockets salinity was the problem and in others residual sodium carbonate was the problem (Table 5). The more saline areas are concentrated in northern Gujarat. Shah *et al.* (1966) reported that in the Santalpur-Mehsana District of this region, ground-water salinity was a problem in the areas closer to the sea and high residual carbonate was a problem in areas farther inland. Salinity due to the proximity of the seacoast is seen affecting sizeable areas also in the Bulsar, Jamnagar, Surat and Kaira districts.

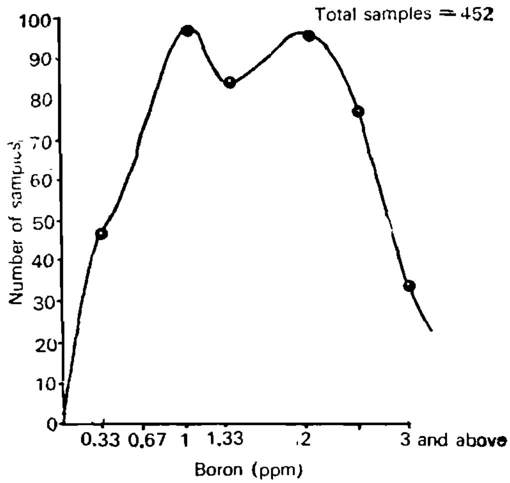

Fig. 1. Frequency distribution of boron in ground-waters of Rajasthan (Paliwal, 1972)

Punjab. Singh and Kanwar (1964) during an exploratory study reported the occurrence of salinity in ground-waters in the relatively arid tracts of the State. In the Ferozepur and Sangrur districts, 54

Table 5. Some mean chemical indices of tube-well waters of northern Gujarat (Talati, 1969)

Salinity class EC	Number of samples	Cations meg/l			Anions meg/l				Residual sodium carbonate meg/l	SAR
		Na^{+}	Ca^{++}	Mg^{++}	Cl^{-}	SO_4^{--}	SO_3^{--}	HCO_3^{--}		
Samples without residual carbonate										
Below 1	36	2·3	3 5	2 0	3·2	0·8	3·6	0 4	Nil	1·4
1–2	133	6·2	4·9	3·5	6·1	1·8	5 4	0·6	Nil	3 1
2–4	34	19·2	7·0	5·3	18·0	5 4	6·8	0·6	Nil	7 6
4–6	20	35·2	7·1	9·5	37·9	7 6	4 6	1·5	Nil	12·9
Above 6	8	74 3	7·9	15·2	74 5	12 3	4·4	4·8	Nil	23·4
Samples with residual carbonate										
Below 1	28	3·3	2 2	1 9	1·6	0·7	3 7	1·6	0 7	2·4
1–2	277	9·5	2·8	2·4	5 4	1·5	4·8	3·2	2 6	4 8
2–4	57	21·2	3·2	14·8	3·0	5·1	4 9	4 9	3·2	12 0
4–6	3	38·2	1·9	7·2	26 4	7 7	3·2	9·6	3 8	22·6
Above 6	11	74 7	2·9	5·8	57·0	9·1	3·0	13 8	8·3	35·7

and 34% of the samples respectively were found to have over 2 mmhos E.C. Bhumbla (1969) found (Table 6) that besides, Ferozepur, the Bhatinda District had salinity hazard, whereas in the Sangrur District, the problem was largely due to high residual carbonate.

Haryana. Like the Punjab State, poor-quality waters in Haryana are also confined to the more arid tracts of the State. The Gurgaon and Hissar districts were shown to have the most serious water-quality problem, as shown by the exploratory studies of Singh and Kanwar (1964). Further detailed studies (Kanwar and Manchanda, 1964; and Uppal and Khanna, 1966) brought out clearly the extent of the saline-water problem in these districts and also in the adjoining Rohtak District. It may be seen from Table 7 that 50 to 60% of the waters of the area have over 2.25 mmhos E.C. in the Jind District, unpublished data of the Central Salinity Research Institute shows that waters with over 2 and 4 mmhos form 50 and 27% respectively. Many waters, particularly in Gurgaon, are found to contain also an extraordinary concentration of potassium and nitrate.

Uttar Pradesh. The bulk of the State is fortunately free from the saline-water problem. Of the eighteen districts, saline water occurs in the Mathura and Agra districts and to a limited extent in the Etah and Aligarh districts (Mehrotra, 1969; Tripathi *et al.*, 1969). In Agra and Mathura (Table 8), water with over 2.25 mmhos EC form 47% and 53% of the total samples analysed. The waters in this range are typically of the chloride-sulphate-bicarbonate type, with negligible or slight residual sodium carbonate. The sodium-adsorption ratio varies, with a vast range of 2 to 24. A more detailed study of the Agra District (Narain *et al.*, 1976) showed that of the 471 water samples 29%, 30% and 25% occur in the EC ranges of 2-6, 6-10 and over 10 mmhos respectively. Nearly 24% samples had over 2.5 m.e. residual sodium carbonate. The boron content was less than 2 ppm.

Besides the above States, there are pockets of problematic waters in Andhra Pradesh, Karnataka and Tamil Nadu. The analysis of 114 ground-water samples from the Challakere *taluka* in Karnataka showed that 66% of the samples had EC between 0.75 and 2.25 mmhos. Though

Table 6. Mean quality indices of ground-waters in some problematic areas of the Punjab State (From Bhumbla, 1969)

District	Number of samples tested	Conductivity in micromhos/cm	Cl^- me/1	SO_4^{--} me/1	Na^+ me/1	SAR	RSC
Ferozepur	1,702	2,062	5·8	5·8	14 8	8·7	3·37
Bhatinda	1,151	2,668	10·7	5·0	18 5	9·1	2·72
Sangrur	400	1,521	13·7	10 6	11 7	8·1	8·00

Table 7. Frequency distribution of some well waters of Haryana in different salinity classes (Uppal and Khanna, 1966) (%)

EC classes micromhos/cm	Rewari, Gurgaon district	Jhajjar, Rohtak district	Bhiwani, Hissar district	Mohindergarh	Narnaul	Dadri
				Mohindergarh dist.		
250	Nil	Nil	Nil	Nil	Nil	Nil
251–750	6·0	Nil	Nil	6·4	4·7	5 6
751–2250	35·3	38·9	31 0	50·3	45·6	31·9
2251–5000	28·0	30 3	48 3	28·8	30·0	33·2
5000	30·7	30·8	10·7	14·5	10·7	29·3

Table 8. Frequency distribution of ground-waters of some districts in Uttar Pradesh in different salinity ranges (After Tripathi *et al.*, 1969)

Range of EC in mmhos	Percentage distribut on of samples in different districts			
	Agra	Aligarh	Etah	Mathura
0·25–0·75	4·2	20 9	55 8	7·7
0·75–2·25	47·9	74·6	40 0	35·6
2 25–5·00	23·2	4·5	3 4	34 6
5–10	15·5	—	0·8	16·3
Above 10	9·2	—	—	5·8
Total number of samples	142	134	120	104

SAR was low, over 90% of samples had residual sodium carbonate with a maximum of 15 m.e/l and a mean of 4.3 m.e/l. In the neighbouring Andhra Pradesh also, the ground-waters presented a similar picture. In Coimbatore in Tamil Nadu (Balasundaram *et al.*, 1969), well waters have salinity range of 0 8 to 4.7 mmhos EC. The coastal area of the State also has the problem of water salinity.

EFFECT OF SALINE WATER ON SOIL PROPERTIES

The potential of saline waters to cause profound, often adverse, effect on soil properties has prompted many studies, both in the laboratory and the field on the role of individual cations, their ratios and the total salinity of irrigation waters on various properties of the soils. Kanwar and Ram Deo (1969) found, by varying the composition of the leaching solution, that in causing adverse effect on soil permeability, potassium acted more like sodium, though at lower concentrations its presence helped to check sodium adsorption. Magnesium in monovalent ratios of 0.2 to 2, behaved closer to sodium but at higher ratios its effect was similar to that of calcium. Likewise, Paliwal and Maliwal (1971) also found that in sodium-dominant waters, the partial replacement of calcium by magnesium in the leaching solution led to an increased adsorption of sodium by the soil. Since the arid-zone waters have not only an appreciable amount of magnesium but also that magnesium generally dominates over calcium, they inferred a greater sodium adsorption on soil than what would be predicted by well-known sodium adsorption ratio of the USSL staff (1954). Paliwal and Maliwal (1971) also proposed a modification of the well-known USSL equation on the relationship between the sodium-adsorption ratio of the saturation extract and the exchangeable sodium percentage of the soil. Kanwar and Kanwar (1969) found that everything else being equal, the equivalent concentration of carbonate in irrigation water led to greater deterioration of the soil physical properties than the bicarbonate ion.

The amount of sodium adsorbed by the soil from any particular water is also dependent on the nature and content of clay. Ramamoorthy *et al.* (1972), while working with different clays or soils dominated by different clays, observed that by following the inverse-ratio law, the bentonite or montmorillonite-dominated soil attained only 10 per cent sodium saturation, whereas the kaolinite- or illite-dominated soil had 55 and 25 per cent sodium saturation, when irrigated with a water of SAR 14. Paliwal (1972) also reported a differential behaviour of the Rajasthan soils, thus showing the limited application of a common ion-exchange equation based solely on the composition of the soil solution.

However, granting no such major soil-group variation, the sodium-adsorption ratio and salinity remain two important determining characteristics of the irrigation waters. Results of numerous pot and micro-plot studies bring out the relevance of these studies in determining the ultimate salinity and sodicity of soils. The results of Bhumbla *et al.* (1964), Kanwar and Kanwar (1969) and Lal *et al.* (1974) show from pot culture or micro-plot studies with light-to-medium-textured soils that the salinity of the soil is primarily governed by the salinity of the irrigation waters and only secondarily by the sodium-adsorption ratio. Realizing the limitation of such studies, more emphasis in recent years has been on larger plots or on cultivators' fields. Singh and Kanwar (1964) found that with irrigation waters of 0.2 to 4.0 mmhos EC, 6-12 SAR and some residual carbonate, the salinity of the soil-saturation extract (ECê) was generally lower than that of the irrigation water. The sodium adsorption ratio of the soil extract was correlated significantly with the residual carbonate of the irrigation water. Likewise, Lal and Lal (1976) in a survey of light-textured soils, irrigated with waters of 0.5 to 4 mmhos EC and 2 to 20 SAR, found that the ECê of the soil was only 63% of the irrigation water, with a near unity relationship between the soil exchangeable sodium percentage and the sodium adsorption ratio of the water. Tripathi *et al.* (1971) and Paliwal and Gandhi (1969) with similar soils also did not observe any salinity build-up even with the use of more saline waters. Kanwar and Mehta (1970) observed in soils having 18 to 44% silt plus clay that ECê was much higher than the EC of the irrigation water. Paliwal and Maliwal (1968) similarly observed that in medium- and heavy-textured soils in Rajasthan, the use of highly saline sodic waters had led to 1 to 7 times more salinity in the soil than that in the irrigation water. The average was 2.79 times. Thus it appears that the soil texture and drainage are very important factors in determining the salinity status of a soil irrigated with a particular water. However, where drainage is not a problem, Singh and Bhumbla (1968) found the following relationship:

Table 9. Relation between EC of irrigation water and saturation extract of soils (Singh and Bhumbla, 1968)

Clay content of the soil	Correlation 'r'	Regression equation
Less than 10%	0·64	$EC_e = 0{\cdot}43\ EC_i + 0{\cdot}47$
10–20%	0 61	$EC_e = 0{\cdot}77\ EC_i + 0\ 19$
20–30%	0·86	$EC_e = 1{\cdot}52\ EC_i + 0{\cdot}75$

Gupta and Abichandani (1968, 1970) observed six long-established sites under irrigation with waters of 3.4 to 8.9 mmhos EC and 12 to 32 SAR and found that salinities of 4 to 12 mmhos ECê were attained at harvest time in March. After the rainy season, during which 350 to 450 mm of rain was received, the bulk of the accumulated salinity was leached down, leaving the top 40 cm of the soil only moderately saline, with ECe values less than 2 mmhos.

Besides the salinity regime, irrigation with saline waters also affects the alkali conditions in the soil. Shankarnarayana and Ganu (1963) and Gupta and Abichandani (1968) found that soils under irrigation with saline waters of SAR 15 to 40 turned saline sodic with exchangeable sodium percentage values of 16 to 59. Singh and Bhumbla (1968), Singh and Lal (1967) and Lal and Lal (1976) also found a similar build-up of alkali hazard in soils with the SAR_e of the soil comparable with the SAR of the irrigation water. Tripathi *et al.* (1971), however, observed a correspondingly small build-up in light-textured soils in the Agra region. Paliwal and Gandhi (1969), Mehta (1970) and Paliwal and Maliwal (1971), however, observed a considerable variability in the soluble sodium percentage and the SAR of the soil extract and the irrigation water. Though a positive relationship was found, the degree of determination was so low that it had hardly any prediction value.

Boron, as has been shown earlier, is present in appreciable quantities in the arid-zone waters. Because of the great sensitivity of crops to an excess boron concentration, boron accumulation in irrigated soils has received considerable emphasis. Singh and Kanwar (1964) did not observe a very significant correlation between the boron content of the irrigation water and that of some soils showing 10 to 20 times more soluble boron. They attributed the variability to the drainage conditions and the mineralogical makeup of the soil. Mehta and Paliwal (1973) observed that the relative boron accumulation was 1.84 times in the irrigation water for heavy-textured soils, 1.44 times in medium-textured soils and 1.27 times in light-textured soils. Likewise, Jain and Saxena (1970) and Moghe and Mathur (1966) also observed an appreciable build-up of boron in the irrigated soils of Rajasthan. The available boron in the soil mostly varied between 1 and 4 ppm, with an average of 3.22 ppm. This value was high, according to the usually accepted norms, but it did not adversely affect the growth of the common crops of the area. In sandy soils, Lal and Lal (1976) did not observe any boron build-up after many years use of water. Mehta (1970) found in equilibrium studies that the increasing concentration of other soluble salts in a constant boron solution caused a decreased adsorption of boron. He, therefore, concluded that the sites of boron adsorption were also available to other constituents in the saline-sodic waters.

SALINE WATER USE AND CROP GROWTH

Massive data are available in the country on the salt tolerance of crops and their varieties at the time of germination. By far, a majority of the data are based on the usual filter-paper-bed technique which does not take into account changes in salt and moisture contents, to which the seeds are exposed under field conditions. Subject to this limitation, the results of the studies can be broadly summed up in that with most field crops, with the exception of a few clovers, seed germination is not a problem under irrigation-water salinity levels at which satisfactory crop growth and maturity are possible. However, vegetable crops, particularly some varieties of brinjal, tomato and cabbage, are sensitive at the germination stage. Maliwal and Paliwal (1970) observed that in influencing germination, the effect of salinity was far more pronounced than that of the relative proportion of sodium to other cations or the sodium-adsorption ratio of the solution.

Interesting work has been done on the growth and yield behaviour of crops in relation to the irrigation-water salinity. With high-salinity waters, i.e. those above 5 mmhos EC, wheat is by far the commonest crop. Bhumbla *et al.* (1964) observed that wheat yield decreased only by 5 and 30% of that obtained with water of EC 3.3 mmhos with increasing salinity of water up to 5.6 and 11 mmhos EC respectively. With a further rise up to 20 mmhos, the yield fell sharply. The SAR of the waters varied from 4 to 16 and its effect on yield was negligible. Tripathi *et al.* (1971) observed in a long-term study that an excellent crop of wheat could be taken continually on a sandy-loam soil, with a water of 2.7 mmhos EC, 9.1 SAR and 3.1 m.e. RSC. Similarly, Lal and Singh (1973) observed a good growth of wheat on a loamy-sand soil, with water of 3.45 EC, 16.7 SAR and 7.2 me/1 RSC or another water of 7.2 EC, 36.1 SAR, but with no residual carbonate. However, with a water of 10.5 EC, 36.1 SAR, the yield was reduced nearly by half. Maliwal *et al.* (1972) found that the yield of wheat decreased roughly by 12, 33 and 66% respectively from the maximum with waters of 7, 15 and 20 mmhos EC. They also found that among different varieties, Kalyansona and Kharchia 65 were more tolerant than Sonara 64 and S-227. The present author's work at Jodhpur, on the other hand, showed that variety Kharchia 65 was more tolerant than Kalyansona, the difference being mainly due to the tiller number. Table 10 gives the agronomic characteristics and yields of the two varieties.

The results show that a better performance of Kharchia is largely due to its larger number of effective tillers.

Field observations on sites under the prolonged use of saline water give a better index of crop growth in relation to the quality of water. Kanwar (1961) and Kanwar and Manchanda (1964) recorded that in the arid tract of Haryana the waters of 15 mmhos EC and 15 SAR were producing bumper crops of wheat. He attributed the success to the light texture of the soil and high nitrate and potassium contents of the irrigation water. Moghe (1968) also reported yields of 20 to 30 q/ha with waters of 7–10 mmhos EC and 18 to 32 SAR on soils of medium texture. Paliwal and Maliwal (1968) observed in the arid and semi-arid tracts of Rajasthan good growth of wheat with waters of 5 to 9 mmhos EC and 11 to 20 SAR. In the case of barley, similar yields were obtained even with higher-salinity waters. Dhir *et al.* (1975) observed that at long-established saline-water-irrigated sites, yields of 15–20 q/ha could be obtained with waters up to 10 mmhos EC, and yields of 10 to 15 q/ha with waters of 10 to 15 mmhos. The presence of nitrate above 1 m.e./1 was significant in raising the yields still further.

Paliwal (1972) and his associates have recorded the relative tolerance of mustard and vegetable crops. The yield of mustard decreased by only 6% at EC 7 mmhos and by 26% at about 15 mmhos EC. Among vegetable crops, cabbage, radish and spinach proved to be most tolerant and showed negligible decreases in yield up to 9.5 mmhos.

With low-salinity waters, i.e. those below 5 mmhos, field crops perform obviously better. However, such waters in the arid zone are used for more economic crops. The author's observations show that waters in the range of 0.75 to 2.25 mmhos EC and with SAR up to 10 are eminently suited for chillies, coriander, cumin and plantago. With a rise in the SAR or with the presence of residual carbonate between 2.5 and 7.5 m.e/1, plantago still grows well, but the yields of chillies, coriander and cumin are reduced by 50%. With waters in the EC range of 2.25 to 5 mmhos, plantago and lucerne grow successfully, but the yields of chillies and cumin fall by 75 to 40% of the maximum. Lucerne grows well with the SAR of 25 or with the residual carbonate above 5 m.e/1. In all these cases, the land is left fallow during the early part of the rainy season.

Table 10. Agronomic characteristics of the two wheat varieties as affected by salinity of irrigation water (1972–73)

EC mmhos	Mean yield in q/ha		Number of effective tillers*		Average number of grains/ ear		1,000-grain weight		Grain protein** in %	
	K 65	K.S.	K 65	K.S.	K 65	K.S.	K 65	K.S.	K 65	K.S.
4	32·3	28·4	2·75	1·91	26·25	32·83	34·35	33·91	12 90	12·10
8	31·0	24·4	2·76	1·75	26 07	31·19	33·96	32·55	13·22	12 93
12	20·3	16 0	1·99	1·51	23 64	24·23	31·46	28·44	13·11	13 00
16	9·6	6 9	1 42	1·26	12·93	14·08	24·94	23·20	12·73	12·62
Mean			2·23	1·61	22·18	25·58	31·18	29·53	12·99	12·66

* = Mean of 105 plants each; C.D. for salinity at 1% level = 0.17; C.D. for varieties at 1% level = 0.09.
** = N × 5.75.

Water-quality classification of ground-waters

A major effort on the part of the USSL staff (1954) on water-quality criteria and suitability classes have given a big impetus to the characterization and assessment of surface and ground-waters. Numerous laboratory studies have since corroborated the general validity of the principles enunciated in this monumental work. Not going into further details of these studies, only some modifications based on the native experience in respect of the original classification of the USSL staff (1954) are discussed here. Kanwar (1961), after observing that even highly saline waters, far beyond the suitability range of the above classification, were being used successfully in Haryana and also in parts of Africa (Durand, 1955), modified the scheme to extend the suitability of waters up to 20 mmhos EC on light-textured soils for salt-tolerant crops. For similar crops on clayey soils, waters up to 2.25 mmhos EC only and with low sodium hazard were suitable. Ramamoorthy (1964) slightly modified the salinity classes by extending the salinity limit of class C_4 to 6.75 mmhos, keeping C_5 in the range of 6.75 to 20.25 mmhos EC. He allotted ratings to soil texture, SAR and EC of the irrigation water and salt-sensitivity of crop.

Mehta *et al.* (1969) realizing the feasibility of using highly saline water in the arid environment extended the suitability of waters to 12 mmhos, provided the SAR was very low.

With the availability of more data on the performance of crops under saline-water irrigation (Paliwal and Maliwal, 1968; Shankaranarayana *et al.*, 1965; Gupta and Abichandani, 1968; Moghe, 1968 and others) it became evident that highly saline waters could be used successfully even on medium- and heavy-textured soils. Also in the vast salinity range of C_5 class of the previous workers, the performance of even tolerant crops varied greatly. At the same time, a need was felt to gather more data on the performance of crops and on the properties of soils irrigated with saline waters. Till the time that data become available, a group of workers in the field assembled in 1972 and reached the following consensus on water quality (Table 11)

Investigations into the use of highly saline waters in a *cyclic management system*

Results are presented here of a medium-term study during which nearly thirty sites, covering a large range of waters and soil textures, were regularly monitored for salinity and alkali hazards in the soil and for crop growth. The sites under study were located in the Pali District, with a mean annual rainfall of 415 mm received almost entirely during the monsoon from mid-June to September. Irrigation is from dug wells and wheat (variety Kharchia) and barley are the common crops. During the growing season, 30 to 40 cm of water is applied. The crop is grown in a cyclic management and after harvesting it, the land is left fallow for one to two rainy seasons, and this respite amounts to fallows of seven and nineteen months respectively. So as not to leave the well idle, the holding is divided into the parcels, each receiving water in alternate years. The sites have been under irrigation for over 10 years and some for as long as 50 years. The texture of the subsoil is silty clay loam or finer at six sites, loam to clay loam at nine, sandy loam to gravelly loam at eleven and sandy at two. The depth of the soil is 40 to 80 cm, below which there is a concretionary or gravelly layer. The water-table is seven to twenty metres.

Characteristics of irrigation waters. Of the 28 sites, 16 have E.C. between 5 and 10 mmhos, 10 between 10 and 15 mmhos and 2 above 15 mmhos. Among the cations, sodium is by far the dominant cation, followed invariably by magnesium and then by calcium. Sodium adsorption ratio is mostly between 15 and 35. Among the anions, chloride is most dominant one, followed generally by sulphate. The residual sodium carbonate is absent in all cases.

Table 11. Water quality ratings (Bhumbla and Abrol, 1972)

	Nature of the soil	Upper permissible limit of E.C. in micromhos of water for the safe use for irrigation of crops	
		Semi-tolerant	Tolerant
1.	Deep black soils and alluvial soils, having a clay content more than 30 per cent. Soils that are fairly to moderately well-drained	1,500	2,000
2.	Heavy-textured soils, having a clay content of 20–30%. Soils that are well-drained internally and have a good surface-drainage system	2,000	4,000
3.	Medium-textured soils, having a clay content of 10–20%. Soils that are very well-drained internally and have a good surface-drainage system	4,000	6,000
4.	Light-textured soils, having a clay content of less than 10%. Soils that have excellent internal and surface drainage	6,000	8,000

N.B. For the above-proposed limits, satisfactory internal drainage and water-table below 1.5 metres at the site, with the soluble sodium percentage of irrigation water below 70 per cent, are assumed.

Salinity build-up during the irrigation phase. At the start of the irrigation phase of the cycle, the entire profile of the soils up to the loamy texture and up to the upper 40 cm of the heavier soils mostly have the saturation-extract values of 1.2 to 2.5 mmhos EC. Salinization progresses with the advancement of the season, and towards the close of the system, the soils show a huge salinity build-up. Salinity is distributed throughout, with a weak maximum at a soil depth of 0–20 or 20–40 cm. Data on the range and the mean value of the saturation-extract salinity at harvest time in the top 40 cm of the soil thickness for different years in relation to the mean salinity of the irrigation water and the texture of the subsoil are presented in Fig. 2. The results show that with the irrigation-water salinity between 5 and 17 mmhos, the soil at harvest time attains 4.5 to 14 mmhos EC of the saturation extract with just one season's irrigation. The magnitude of salinity build-up rises with the increasing salinity of the irrigation water and the texture of the soil.

Salinity changes during the fallow phase. As stated earlier, a particular parcel after the crop has been harvested is left fallow during the ensuing rainy season and, in most cases also, for one more year, or till the second rainy season. Salinity changes during the fallow period were followed by a depth-sampling of the soil after each rainy season. Results obtained from different sites grouped according to the texture of the soil for different years are presented in Table 12. In preparing this Table, leaching of the salts has been worked out as the percentage loss after one or two rainy seasons, as the case may be, of the accumulated salts. The accumulated salinity is the salinity added during a particular irrigation season, i.e. the difference between the salinity that the soil had at the start and the close of the irrigation season. The figure of over 100% leaching shown in some cases is due to the fact that in this particular situation not only all the salinity added during the preceding irrigation has been taken care of, but also the residual salinity, particularly in the 40–80-cm depth, the soils generally, have at the start of the irrigation season. Results (Table 12) show that in 1971 and 1972, each of which received only 60% of the mean annual

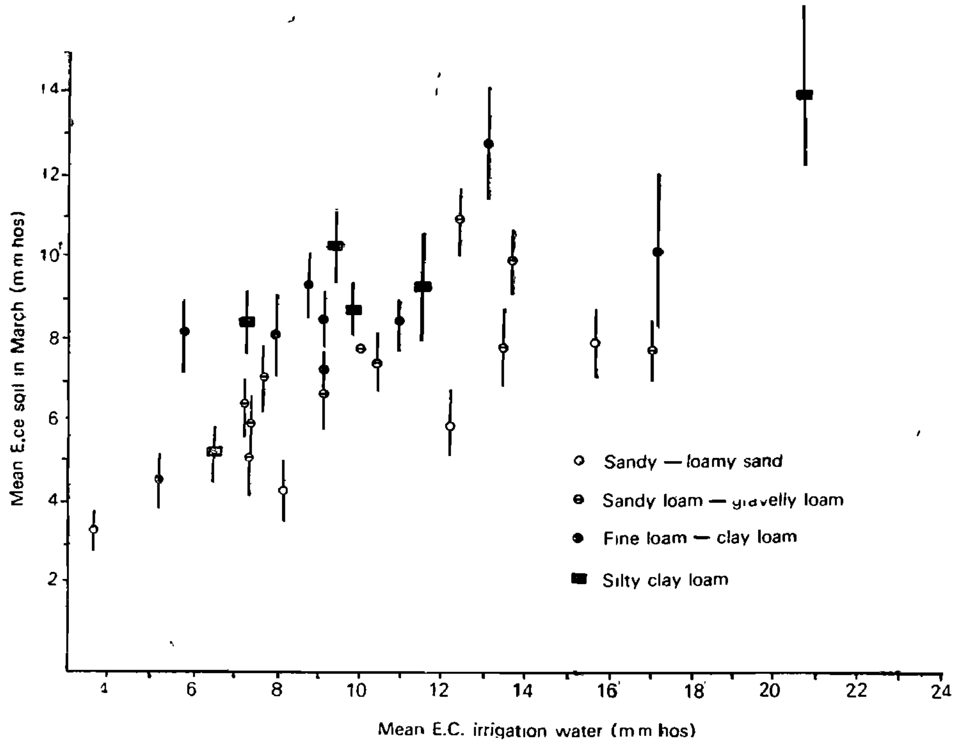

Fig. 2. Mean salinity build-up in 0.04-cm soil layer in relation to its texture and mean salinity of irrigation water for the period 1970-73 at different sites

rainfall, complete leaching from one year's rainfall occurred only in the loamy-sand site. In the sandy-loam sites, 80% of the accumulated salinity was lost from the top 40-cm layer. On heavier soils, desalinization was of the order of 50–80% for this depth. During 1970, which received 142% of the average rainfall, the complete leaching of accumulated salts was achieved in all soils except in the silty clay loams. In the latter, the leaching from the 0–60-cm depth was 70% only. An exceptionally wet year, such as 1973 (twice normal) alone was enough for the complete leaching of all accumulated salts from the soils of all textures. As seen from the figure of over 100% during this year, even the residual salinity that is often present at 40–80-cm depth was leached down, besides that added during a particular irrigation season.

A fallow for the second year led to progressive leaching and was particularly significant when the preceding rainy season had been below the average. Rains of two consecutive drought years of 1971 and 1972 were enough to wash down salinity from the 0–40-cm depth from sites of all textures. The foregoing results clearly show that the huge salinity build-up of the irrigation season is taken care of by one above-average year's rainfall or two subnormal rainy seasons. Some salinity is retained at the 40–60-cm soil depth, particularly in clay-loam and heavier soils, but this condition has not been found to interfere with re-use of the land.

The alkali hazard in soils. The alkali hazard was measured in terms of exchangeable sodium in the soil at different phases of the cycle. The results showed a large intersite as well as a cyclic variation. At

Table 12. Natural leaching of accumulated salts during the fallow period due to rainfall at different sites grouped according to the texture of the subsoil (data expressed as percentage loss of salinity accumulated during the preceding irrigation season)

S. No.	Year		1970	1971		1972		1973		1974
	Annual rainfall(mm)		596·5	276·8		239·3		892·6		201 5
			One-year fallow	One-year fallow	Two-year fallow	One-year fallow	Two-year fallow	One-year fallow	Two-year fallow	Two-year fallow
	Total amount of rainfall (mm) received during the fallow period	Depth (cm)	596 5	276·8	873 3	239 3	511 5	892·6	1131 9	1,094·1
	Textural group									
1.	Silty clay loam	0–20	78	81	101	85	91	102	119	132
		0–40	73	53	100	60	73	120	144	152
		0–60	72	36	96	44	50	153	148	159
2.	Fine loam to clay loam	0–20	103	67	95	89	94	115	107	105
		0–40	102	53	99	82	88	116	107	125
		0–60	99	45	83	59	70	118	122	150
3.	Sandy loam to gravelly loam	0–20	107	93	102	96	100	96	113	107
		0–40	104	86	101	82	95	102	116	107
		0–60	102	65	—	73	88	107	108	117
4.	Sandy to loamy sand	0–20	113	100	125	100	—	—	—	—
		0–40	110	98	105	94				
		0–60	116	96	96	90				

harvest time, the soils had 1.3 to 7.2 me/100 g of exchangeable sodium which constituted 14 to 53 % cation-exchange capacity of the soil with the subsoil generally having somewhat higher values than those of the upper 20-cm soil layer. The values in the top 20-cm layer at this stage corresponded very closely with what were predicted by the sodium-adsorption ratio of the irrigation water. Samples collected during the fallow phase showed a distinct decline in the exchangeable sodium, particularly in the top layer. In all cases but one, the values were much lower and in one case against a value of 6 1 me/100 g, the value reached after desalinization was only 1.6 me/100 g. Figure 3 shows the mean values of alkali hazard prevailing in the soil in relation to those predicted from the sodium-adsorption ratio of the irrigation water. The results interestingly show that the fallow period, besides leaching the salts led to a significant lowering of the alkali hazard at the 0–20-cm soil depth. A subsampling of 0–20-cm layer at some of the sites (Table 13) brought out this phenomenon even more spectacularly. The exchangeable sodium percentage values at the sites after natural leaching during the fallow phase were incredibly lower than what had prevailed at the peak of salinization phase. In fact, the top layer in many cases was not even characteristically sodic after leaching. This favourable trend in the soil was found to be related to the presence of calcium and sulphate in the irrigation water. They got accumulated more in the surface layer. Results in Table 14 for some of the sites clearly show that in comparison with the composition of the irrigation water, the soil-saturation extract had proportionately a much larger concentration of calcium and a lower concentration of magnesium than those in the irrigation water. Thus during irrigation and the accumulation of salts, there is a differential accumulation of calcium. In the 0–10-cm layer, the concentration of $CaSO_4$ at this time in the saturation extract was of the order of 25 to 45 m.e/1, which was many times more than that present in the irrigation water. However this concentration did not markedly lower the sodium-adsorption ratio at this stage, as the amount of magnesium was correspondingly less. Thus the already stated extraordinarily low values of exchangeable sodium after natural leaching, on the one hand, and a greater accumulation of calcium, on the other, strongly suggest that during leaching, there is a selective leaching of the accumulated salts, leading to a greater retention of calcium sulphate and its subsequent interaction with the soil.

The foregoing results very clearly show that the use of highly saline water does lead to a high level of salinity even after one season's irrigation, but this build-up is not permanent and is amenable to leaching through rainfall. Second, the use of highly saline sodic waters has also not led to a permanent build-up of exchangeable sodium. In fact, in the 0-20-cm layer, the values of alkali hazard prevailing during the fallow phase are much lower than what could be predicted from the sodicity of the irrigation water.

Crop growth: Wheat (variety Kharchia) and barley are the common crops under the use of highly saline water. The lands are dry-seeded at the rate of 1.5 to 2 q/ha and then irrigated. In the course of a

Table 13. Alakali hazard in the soil of some sites at different phases of saline water cycle

Depth in cm	Exchangeable sodium in soil (me/100 g)		Depth in cm	Exchangeable sodium in the soil (me/100 g)	
	Crop at harvesting time	At the close of the fallow phase		Crop at harvesting time	At the close of the fallow phase
1	2	3	4	5	6
	Site 1			*Site 6*	
0–5	2 7	0·36	0–5	2 63	1·23
5–10	2·9	0 68	5–10	2 62	2·11
10–20	3·0	1·74	10–20	2·32	4·10
20–40	4·4	4·50	20–40	3 88	4·28
	Site 4			*Site 17*	
0–5	5 76	2·21	0–5	3·36	0 27
5–10	5·31	4·56	5–10	3 64	0·80
10–20	5·25	8·79	10–20	3·84	1 54
20–40	9·13	11·10	20–40	4 09	3·64
40–60	11 28	11 20	40–60	4 18	4·73
	Site 18			*Site 41*	
0–5	2 23	0·21	0–5	4 82	0·7
5–10	2·24	0 44	5–10	4 22	1·10
10–20	2·42	0·38	10–20	4·42	1·86
20–40	3·92	2 97	20–40	5·36	3·66
40–60	3 44	2·91			
	Site 26			*Site 43*	
0–5	3·18	0·42	0–5	2·21	0 84
5–10	3·24	0 53	5–10	2·32	1·28
10–20	3·20	1·80	10–20	2 45	2 15
20–40	4·99	2·78	20–40	2·80	2·67
40–60	4·17	3·16	40–60	3·29	2 11

Table 14. Percentage ionic composition of irrigation water and saturation extract of soils of some sites at the time of harvesting the crop

S. No.	Soil depth	Na	Ca	Mg	Cl	HCO_3	SO_4
1	2	3	4	5	6	7	8
1	I.W	80·8	9 1	10·1	44·2	9·5	46·3
	0–5	77 9	14·7	7 4	49 9	5 0	45·1
	5–10	80·9	13 5	5·6	40·3	4·3	55·4
	10–20	84 3	10 0	5·7	51·2	3·7	45·1
	20–40	83 2	6·2	10 6	30 5	3·5	46·0
4	I.W	86·4	4·4	9·2	81·3	8 7	10 0
	0–5	89 6	5·1	5·3	74 1	7·1	18·8
	5–10	87·3	5 3	7·4	78·1	4·5	17·4
	10–20	87·2	3·6	9·2	81·8	2 9	15·0
	20–40	91·2	2·3	6·5	81 7	3·1	16·2
	40–60	93·6	2·1	4 3	74·1	4·9	21 0
6	I.W	61·3	9·7	29 0	86·6	4·0	10·4
	0–5	60 9	21·3	17 8	87·8	1 6	10 6
	5–10	67 0	15 2	17·8	88 8	3·1	8·1
	10–20	59·7	17·8	21·5	83·8	2 5	13·7
	20–40	74·6	9·0	16·4	94 2	2 4	3·4
	40–60	82·3	6·4	11·3	95 2	2·3	2·5
17	I.W	69·2	15·2	15·5	60 0	3·0	37 0
	0–5	70 2	21 2	8·6	63·2	—	36·8
	5–10	65·7	23·0	11 3	56 6	2 6	40 8
	10–20	65·6	23·8	10·6	58 7	1·9	39·4
	20–40	73·9	16 6	9·5	71 1	3 9	25·0
	40–60	76·0	14·1	9·9	62·8	3·1	34·1
43	I.W	69·3	11·1	19·6	58·8	4·1	37·1
	0–5	69·0	18·4	11·6	60·9	1·4	37·7
	5–10	62 8	23 5	13 7	54 3	3·8	41·9
	10–20	68·9	19·2	11·9	65 6	2·0	32·4
	20–40	76 3	10·5	13 2	71·6	5 1	24·3
	40–60	80·4	10 6	9·0	81·6	7·4	11·0

season, 30 to 40 cm of water is applied as 6 to 8 irrigations. The visual manifestations of salinity stress are the reduced height of the plants and the tip burn of the lower leaves. However, the yields are fair. The results of crop yields for different years are shown in Fig. 4. Good, average and poor yields correspond to over 15, 15 to 10 and below 10 q/ha grain yield respectively. The results show that with the EC of irrigation water below 10 mmhos and the EC of the saturation extract of the soil at harvest time below 11.5 mmhos, the yields are good to average. Of 44 observations in this group, 27 were rated as good, 16 as average and one as poor. With the EC above 10 mmhos, but the EC_e still below 11.5 mmhos, the yields are mostly average. With the EC_e at the harvest time above 11.5 mmhos, the yields are poor. Exceptions are two sites with the above-average nitrate content. It was seen that waters having more than 1 and particularly 1.5 m.e/l NO_3 resulted in exceptionally good growth.

The results of analysis of the samples of wheat plants collected at the emergence of the ears showed that, though with increasing salinity there was a non-linear increase of sodium content in the plants, the contents of potassium, calcium, magnesium, phosphorus and nitrogen were unaffected. Thus it seems that the saline-sodic environment created by the highly saline waters did not seem to affect the uptake by Kharchia of the essential major nutrients (Dhir and Gajbhiye, 1976).

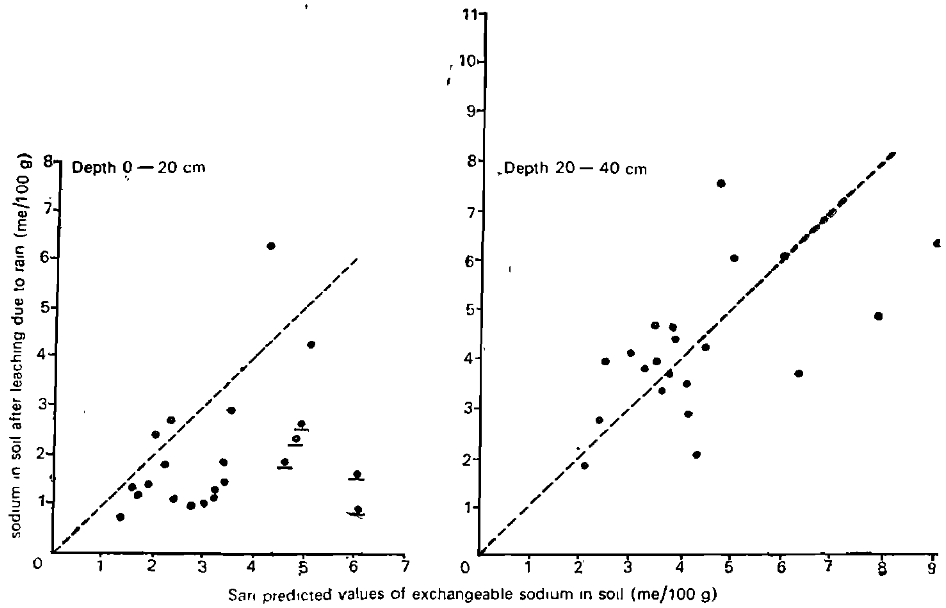

Fig. 3. Exchangeable sodium content in soil during the fallow phase, in relation to exchangeable sodium predicted from sodium adsorption ratio of irrigation water. The underlined dots refer to sites having mostly over 15 m.e./l of calcium

The protein content of the grain also was not seen to be adversely affected by the rising salinity of water.

Use of potentiality of saline waters in arid environment

In evaluating the suitability of saline waters for the arid zone, a few factors deserve special consideration. The adverse-quality waters are often the sole source. Rains are erratic in quantity and distribution and the average yields from the rainfed crops rarely exceed 4 to 5 q/ha.. The farmers are generally without work during winter. Therefore even lower returns, such as may be considered unremunerative in other areas, are acceptable. Further, the sunny and frost-free winters provide ideal growing conditions for a number of commercial crops. The other advantages are that even medium- and heavy-textured soils in most situations have a pervious substratum and the table is low.

Further observations on the saline-water system under field conditions suggest that salinity resulting from the use of sodium chloride-dominated waters is not permanent. In response to rainfall, the salinity is leached fast. In a 400-mm-rainfall area, the salinity build-up is taken care of by one year's rainfall in soils of medium texture and by two year's rainfall in heavier soils. Second, it has also been found that the use of highly saline-sodic waters for lengths of period from 10 to over 50 years has not led to a disproportionate build-up of the alkali hazard. In fact, the cyclic use of waters, such as is feasible with these waters, allows a greater accumulation of calcium, which during the process of natural leaching results in a lower and favourable level of exchangeable sodium in the most important surface layer of the soil. Thus highly saline waters can continue to be used without reservation that their use may lead ultimately to the land getting unfit even for such a system.

Based on the experience gained on the behaviour of crops in relation to the salinity of irrigation water, the potentiality

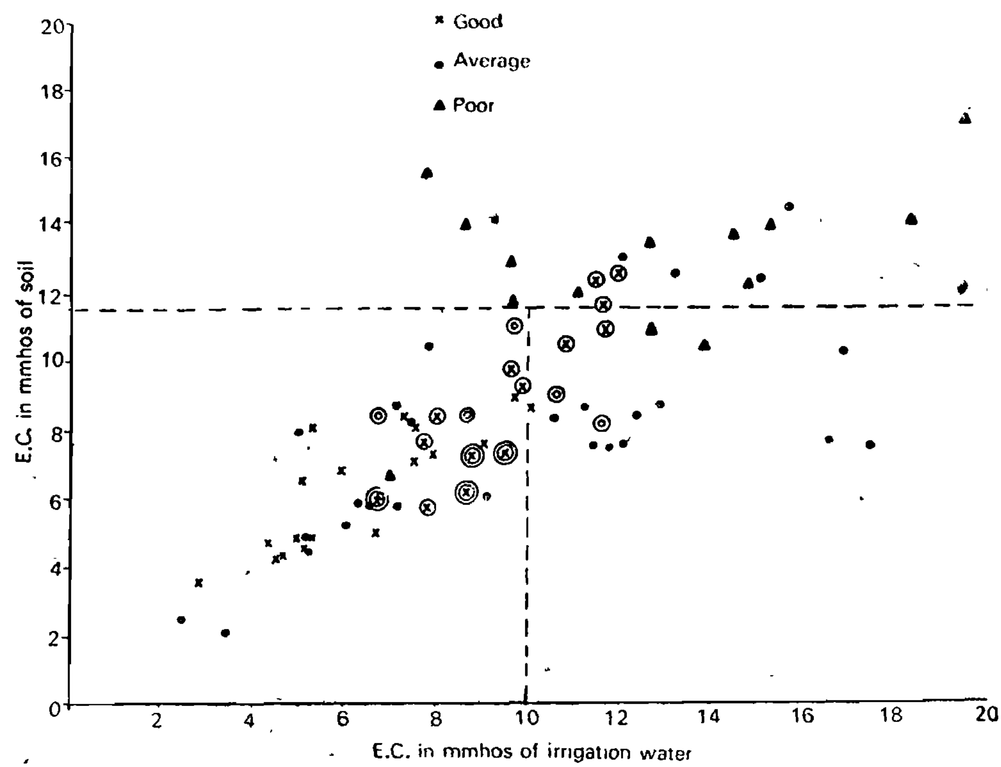

Fig. 4. Growth of wheat at different sites in relation to salinity of irrigation water and soil at harvest time. Good, average and poor mean over 15, 10-15 and below 10 q/ha of grain yield respectively. Single and double circles refer to the presence of nitrate in the irrigation water 1.0 to 1.5 and above m.e./l (Dhir *et al.*, 1976)

EC of water in mmhos	5	10	15
Yield of wheat in g/ha	20	15	10
Frequency of cropping in relation to soil texture			
Up to loamy sand	Double cropping with wheat and *bajra*	Wheat every year	Wheat in most years
Sandy loam to loam	-do-	Wheat in most years	Wheat in most years
Clay loam	Wheat every year	Wheat in alternate years	Wheat in alternate years
Silty clay loam and clay	Wheat in alternate years	-do-	-do-

(N.B. Where waters contain 1 to 1·5 and over 1·5 me/l nitrate, 3 to 5 and 5–7 q/ha yield may be added. Wherever the water contains over 15 m.e./l calcium sulphate or a higher concentration of sulphate with calcium in the range of 8 to 15 m.e./l, wheat is possible in most years even on clay loam soils with water of 10 mmhos EC.)

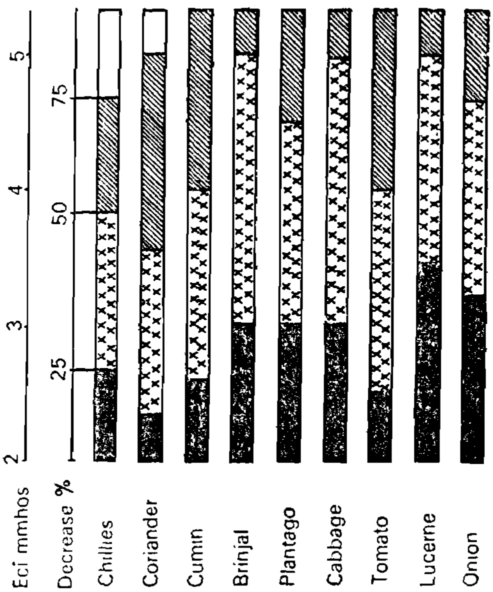

Fig. 5. Growth of different crops in relation to salinity with waters up to 5 mmhos EC on well-drained soils, with fallow during the early half of the monsoon

of various salinity waters is shown in Fig. 5 and in the statement on preceding page.

Fig. 5 is for waters having RSC up to 2.5 m.e./l. Those containing RSC between 2.5 and 7.5 m.e./l reduce the yield of chillies and cumin by 50%, though plantago and lucerne continue to withstand the adverse effects. The maximum yields of chillies, coriander and cumin are 50, 6 and 4 q/ha.

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16

DESALINATION TECHNIQUES FOR CONVERSION OF BRACKISH WATER INTO POTABLE WATER FOR SMALL COMMUNITIES

A. V. RAO AND D. J. MEHTA

THE supply of good-quality potable water to the community is a measure of the degree of civilization which a society can reach, and it is the civic responsibility of those in power to ensure a continued supply of good-quality potable water to the masses. (Table 1). There are many large areas in our country which are deficient in potable water. There are many places in Kutch, Saurashtra, Rajasthan, Haryana, Orissa, Tamil Nadu and Karnataka and, for that matter, in almost every State where people drink brackish water, with salinity ranging from 1000-5000 ppm. An appraisal of the chemical quality of groundwater occurring in varied hydrogeological settings and ecological environments, as revealed through the exploratory drillings, is outlined in a paper by Raghava Rao *et al.* (1971) which covers the information from representative areas in the four regions of the Indian Subcontinent.

(i) The arid tracts of western India, (ii) the semi-arid regions of Rajasthan, partly Gujarat and central India, (iii) the coastal regions from West Bengal to the Madras State, and (iv) isolated patches in Indo-Gangetic alluvium and the inland river valleys where salinity in groundwater is normally expected.

Table 1. U.S. Public Health Service's Standards for Drinking-Water

		Max. ppm
1.	Total dissolved solids (TDS)	500
2.	Chloride (Cl)	250
3.	Sulphate (SO_4)	250
4.	Magnesium	125

Brackish waters generally have sodium chloride in the range of 1000–1500 ppm, with the TDS up to 3,000 ppm, whereas the sea-water falls in the category of very highly saline water in which the TDS is up to 3,5000 ppm. The degree of ionization and the capability of ground-water to take or reject the salts in order to retain its ionic equilibrium are the principal factors governing the waters to become saline or brackish. Moreover, the groundwater is an aqueous solution of carbonates, bicarbona'es, sulphates and chlorides of the alkali and alkaline earth metals.

It has been reported that in parts of the Punjab and Haryana States and in western Rajasthan, the quality of water is highly variable from place to place and the TDS is always above 5,000 ppm. (Raghava Rao *et al.*, 1971) In the Kutch area, the deeper aquifers contain highly saline waters, the TDS being in the range of 3,000 ppm and above. In the Banaskantha and Mehsana districts of western Gujarat, highly saline waters are encountered. In them the chloride content shoots up to 12,000 ppm. The waters occurring in the Saurashtra region are saline and the TDS generally ranges from 2,000 to 5,000 ppm. The coastal areas of the Ramanathapuram district in Tamil Nadu were explored by making bore holes and the data revealed the composition of sea-water. Fig. 1. shows the distribution and extent of salinity of the ground-waters of the arid zone of western India.

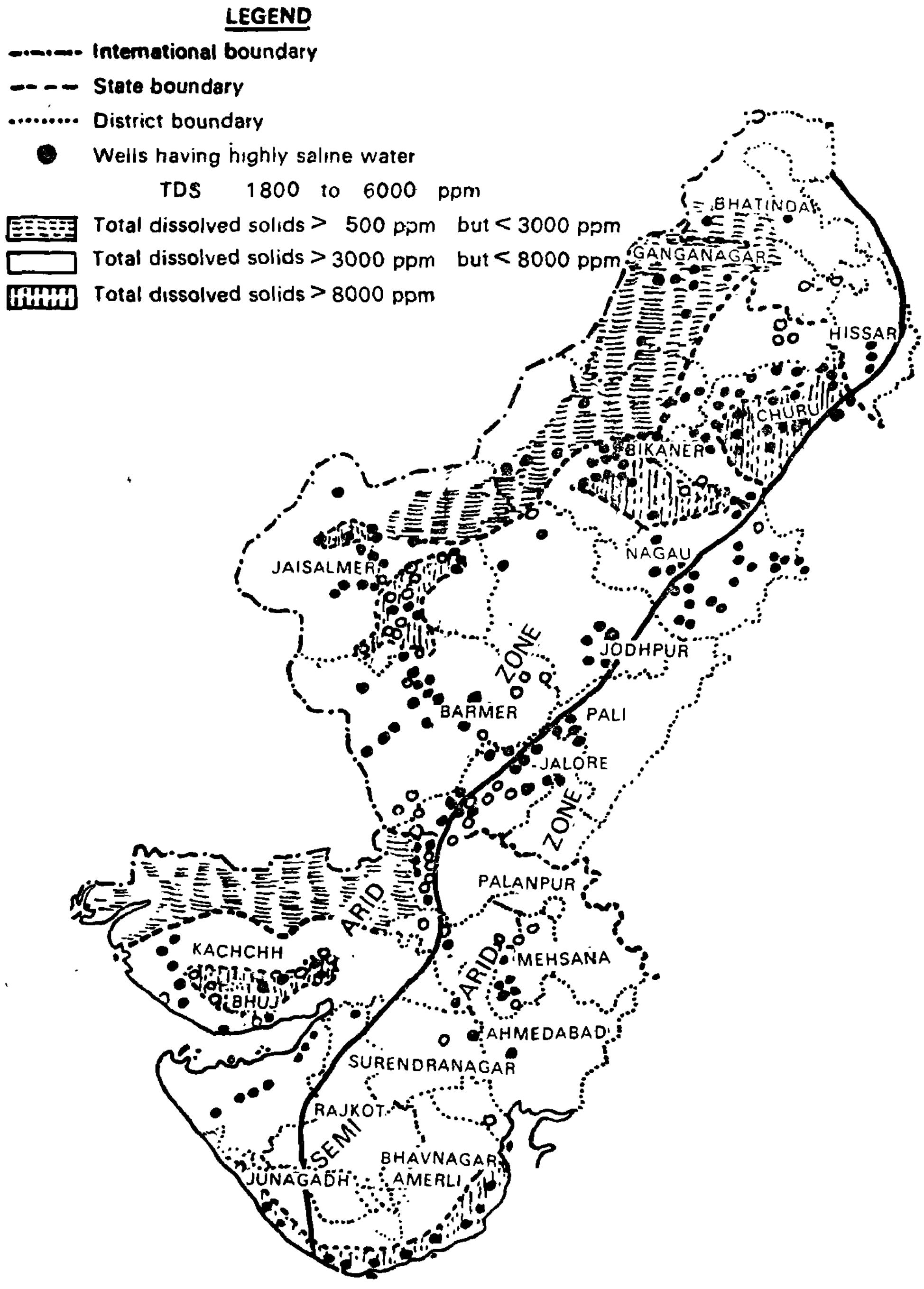

Fig. 1. Distribution and extent of salinity of the ground-water of the arid zone of western India

The ground-waters from three development blocks in the central Luni River basin of Rajasthan have been classified according to their TDS range by Mandal (1964). The classification shows that nearly 45% of the ground-water coverage is in range of 1,500–7,000 ppm. Sometimes, these waters, besides being saline, contain undesirable or injurious chemicals which are responsible for some peculiar diseases. For instance, fluorine in water causes what is commonly known as fluorosis. The continued neglect and indifference on the part of the authorities without paying any attention to solve this problem, in itself, constitutes a civic crime. It is precisely here that they can have recourse to science and technology; adopt techniques which have been developed and solve some of the environmental problems for the welfare of society. The Central Salt & Marine Chemicals Research Institute has developed some desalination techniques which are eminently suited to a given set of conditions. The most important of these techniques are : (1) the use of solar stills, (2) reverse osmosis, and (3) electrodialysis.

Solar stills

Solar stills are ideal for small isolated communities where water requirement is *not much, the needed power is not* available and the water is saline. The transport of water from the neighbouring places is neither easy nor feasible. The advantages of solar stills are that no expendable energy is required; salinity can be to any degree; they are simple in construction and the operating and maintenance costs are small.

Glass-roofed solar stills

A solar still consists of a long, narrow, black tray which holds the salt water and is covered with an A-shaped tent roof of glass with gently sloping sides that end over a trough at each side of the tray. The sun's rays pass through the glass roof and are absorbed by the blackened bottom of the tray which holds about 2.5-cm deep salt water. As the water becomes heated, its vapour pressure increases, the water vapour is condensed on the underside of the roof and runs down into the troughs which conduct the distilled water to a reservoir. The still acts as a heat-trap, because the incoming sunlight passes through the transparent roof, but the roof is opaque to the long infrared radiation emitted by the hot water. The roof encloses all the vapour and prevents its loss and at the same time keeps the wind from reaching the salt water and cooling it. The water wets the glass and gives a smooth transparent film of liquid. Table 2 shows the distribution of solar energy in glass-roofed stills, whereas Table 3 gives the performance of a typical glass-roofed still.

Table 2. Distribution of solar energy in glass-roofed still

	Dec.	May
Reflection	11 8%	11 8%
Absorption by glass cover	4·1	4 4
Loss by radiation from heated water	36 0	16 9
Internal circulation of air	13 6	8 4
Ground and edge losses	2·1	3·5
Re-evaporation, shading, etc.	7·9	14 5
Distillation of water	24·5	40 5

Table 3. Performance of glass-roofed still (Daniels, 1964)

	Dec.	May
Average solar radiation, BTU ft $^{-2}$ day^{-1}	756	2,318
Average solar radiation, Langleys day^{-1}	205	628
Average cover temperature	71°F 22°C	98°F 37°C
Average brine temperature	82°F 28°C	111°F 44°C
Average production gal ft^{-2} day^{-1}	0·021	0 105
(Gal day^{-1} ft^{-2} heat vaporization (8,913 BTU gal^{-1})) / (Solar radiation BTU ft^{-2} day^{-1}) × 100	24%	40%

After extensive studies on both laboratory and pilot-plant scales of 1,000 litres per day, this Institute has gained sufficient experience and expertise in the installation of solar stills of any suitable capacity.

The average output of the still is about 2.5 litres per Sq metre per day. The design developed by the Institute can be adapted for the installation of solar stills on ground or terraces and the construction materials are those commonly employed in building construction. This Institute has also designed solar stills and has helped to install them at (1) Navinar Lighthouse (130-litre-per-day capacity), (2) The Engineering Research Institute, Baroda (80-litre-per-day capacity), besides installing its own unit at the Experimental Salt Farm (1,000-litre-per-day capacity), and another of 100-litre-per-day capacity on the terrace. Recently, this Institute has undertaken the construction of the two solar stills, each 'of 5,000-litre-per-day capacity in two villages in the Gujarat State as part of the general programme to be extended to other States also.

Reverse osmosis

Reverse osmosis is a membrane process in the sense that it employs semi-permeable non-ionic membranes for the purification of water. It is suitable for medium requirements up to 100,000 litres per day. Salinity can be as high as 10,000 ppm. The advantages of the reverse osmosis are: (i) energy costs are only the pumping costs; (ii) it is simple in operation and maintenance; (iii) it finds varied applications in many process industries, involving separation, concentration and purification of chemical species.

In the reverse osmosis, the saline water flows under pressure through a semi-permeable membrane inserted with a suitable backing support in a perforated aluminium tube when the solvent water permeates through the membrane and is collected in a trough. The rejected solute species which get concentrated as a result of the removal of water are carried along with the effluent which is discharged as a waste stream. The heart of the technique lies in the membrane which should behave as an ideal semi-permeable membrane, so that the maximum rejection of the solute species is achieved. At the same time, the membrane should have a reasonably good permeability for water, so that high water outputs (product water flux) could be obtained. Membranes with satisfactory performance have been fabricated from indigenous cellulose acetate and are currently used in our reverse-osmosis plants.

Based on the experience and expertise gained in fabricating the reverse-osmosis plants for drinking-water as well as for industrial separation problems, this Institute has set up one plant of 9,000 litres of potable water per day in the border area (Vigakot) and another of 15,000 litres per day was operated for 3 months at Rajasthali—a village in the Amreli district. Likewise, one plant of 10,000 litres per day was fabricated and demonstrated to the Defence Establishment at Jodhpur, whereas another plant of 1,000 litres per day was supplied to the Sunderban Development Board, Government of West Bengal. One plant of 10,000 litres per day was operated round the clock for 21 days at the Hissar Textile Mills, Hissar, Haryana, on their well water.

ELECTRODIALYSIS

Electrodialysis employs perm selective membranes for the desalination of brackish water. This process is more economical for salinities below 5,000 ppm. The energy costs are directly proportional to the salinity and, hence, beyond 5,000 ppm, reverse osmosis has a distinct advantage over electrodialysis.

Electrodialysis—properly called multiple-ion-exchange-membrane electrodialysis (MIEME)—is a relatively new unit process. In this process, both cation- and anion-exchange membranes are used. The cation-exchange membranes allow only the cations to pass through them, but are virtually impermeable to the anions. Similarly, the anion-exchange membranes allow only the anions to pass through them, with a negligible permeation by the cations. As these membranes are ionic in character, they act as ionic conductors and the ionic transport takes place under the influence of an electrical potential.

By packing the cation- and the anion-exchange mambranes alternately in-between two electrodes, thin chambers are formed with the help of gaskets and spacers, which are non-conducting plastic materials. Any feed-water to be desalted is split into two streams and fed into alternate sets of compartments in the stack. The electrode chambers are separately flushed with the feed-water to remove the products of electrolysis. When a direct electric current is passed through this unit, the ions in solution migrate towards the electrodes of the opposite polarity, but owing to the membrane barriers, the alternate chambers in the stack get depleted in salt content, whereas the remaining chambers get concentrated with salts. The process is made continuous as the concentrated and dilute solutions are drawn out continuously from the system. The most attractive feature of this process is the control on the product water salinity by suitable adjustments of the flow-rate and current input. One plant of 10,000 litres of potable water per day was set up and operated by this Institute for 6 months at a village of Diu and another of 12,000 litres per day was operated for one year at Motagokharwada, a village in the Amreli district. Likewise, one plant of 25,000 litres per day was fabricated and demonstrated to the Defence Establishment at

Table 4. Construction costs of a standard solar still

(20 (m^2) area, 50-lit./day capacity)

Break-up of costs	Rs/m^2
1. Foundation and sand-filling	8·00
2. End and side walls complete with plaster	32 00
3. Still bottom, i.e., plastered masonry with paint	21·00
4. Top support, aluminium tee	4·00
5. Product channel of aluminium	15·00
6. Glass cover fitting with sealing, etc.	30·00
Cost of distiller per m^2	110 00

	Solar still for villages
1. Capacity, litres/day	5,000
2. Area, m^2	1,850
	Construction costs in Rs
1. Distiller unit	2,03,500
2. Storage tank	2,500
3. Blending tank	2,500
4. Raw water storage tank	2,500
5. Shed to house the materials	2,000
6. Hand-pump, pipe fittings, etc.	8,000
Total costs of the unit	2,21,000
Contingencies @ 5%	11,000
Miscellaneous such as visits to the site, etc. @ 10%	22,100
Estimated input per unit	2,54,100

Table 5. Cost of product water from solar stills of 5,000 litres/day capacity

= Life of the still is assumed 20 years

= Annual charges combining depreciation and interest (amortization) is taken as 8·0%

	Annual cost Rs (Basis: 365 days)
1. Amortization @ 8%	17,680
2. Labour charges:	
(i) Operator @ Rs 200 per mensem	2,400
(ii) Additional labour for cleaning and maintenance—100 man-days per year per 1000 m^2; for 1850 m^2; 185 man-days per year @ Rs 5 per man-day.	925
3. Maintenance and repair @ 1·0%	2,210
Total cost of production	23,215
Total production per annum	1825 m^3
Cost per m^3 (1,000 litres)	Rs 12·8
Assuming the blending of distilled water with feed-water in the ratio of 4:1, then daily output is 6250 litres, and cost per m^3	10·2

Jodhpur, whereas another plant of 5,000 litres per day was supplied to the Sunderban Development Board, West Bengal.

The estimated capital costs and the operating costs for plants of 5,000-litre-per-day-capacity of solar stills and 10,000 litre-per-day of reverse osmosis and a electrodialysis are given in Tables 4 to 7, whereas Table 8 summarizes the comparative costs of three techniques.

Table 6. Cost estimates for reverse osmosis desalination plant

Capacity	:	10,000 litres potable water/day
Feed-water salinity	:	5,000 ppm
Product water quality	:	500-1,000 ppm
CAPITAL INVESTMENT		
Principal items (P.I.)		
		Rs
1. Plant module	:	30,000
2. Membrane	:	3,000
3. High-pressure pump	:	17,000
Total P.I.	:	50.000
Subsidiary costs		
4. Instrumentation @ 6% of P.I.	:	3,000
5. Erection & assembly @ 10% of P.I.	:	5,000
6. Contingencies @ 5% of P.I.	:	2,500
Total capital investment (sum of 1 to 6)	:	60,500
OPERATING COST PER DAY		
Items		Rs
1. Energy cost	:	18 00
3. Labour & supervision (one skilled person per shift)	:	30·00
3. Maintenance (2% of C.I.)	:	3·60
4. Depreciation :		
(a) On membrane (replacement every 6 months)	:	17·00
(b) On pump (10%)	:	5·00
(c) On plant (7·5%)	:	7·00
Total operating cost per day (sum of 1 to 4)	:	80·60
∴ Cost of desalted water per 1,000 litres	:	8·06

Table 7. Cost estimates for one electrodialysis desalination plant

Capacity	:	10,000 litres of potable water/day
Feed-water salinity	:	5000 ppm
Product water quality	:	1000 ppm
CAPITAL INVESTMENT		
Principal items (P.I.)		
		Rs
1. Electrodialysis stacks	:	35,000
2. Membrane	:	10,000
3. Pumps	:	3,000
4. Rectifier	:	6,000
Total P.I.	:	54,000
Subsidiary costs		
5. Instrumentation @ 10% of P.I.	:	5,400
6. Erection & Assembly @ 10% P.I.	:	5,400
7. Contingencies @ 5% of P.I.	:	2,700
Total capital investment (C.I.) (sum of 1 to 7)		67,500
OPERATING COST PER DAY		
Items		Rs
1. Energy cost	:	11·00
2. Labour & supervision (one skilled person per shift)	:	30 00
3. Maintenance (2% of C.I.)	:	4 00
4. Depreciation :		
(a) On membrane (20%)	:	6 00
(b) On pump (10%)	:	1·00
(c) On plant (7·5%)	:	8·00
Total operating cost per day (sum of 1 to 4)	:	60 00
∴ Cost of desalted water per 1,000 litres	:	6 00

Table 8. Comparative costs of three desalination techniques

Capacity of the plant:	:	10,000 litres/day of product water
Desalination ratio	:	5

(For R. O. & E. D. plants only)

Cost estimates	Desalination techniques		
	Solar stills	Reverse osmosis	Electrodialysis
I Capital investment Rs in lakhs	5·08	0 63	0·68
II Operating costs Rs per day			
(1) Energy costs	—	18	11
(2) Amortization	97	29	15
(3) Labour and supervision	18	30	30
(4) Maintenance & repairs	12	3	4
(5) Cost per m^3	12·7*	8	6

*Assuming the blending of distilled water with feed water in the ratio of 4:1, then the cost per m^3 is Rs 10.

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17

GROUND-WATER RESOURCES OF THE ARID ZONE OF INDIA

T. N. MEHRA AND AMAL KUMAR SEN

THE great Indian desert, also called the Arid Zone of North-Western India, extends between 22° 30′ N and 32° 05′ N latitude and from 68° 05′ E to 75° 45′ E longitude. In the entire area, the total annual evapotranspiration exceeds the total annual precipitation. Highly unfavourable hydrometeorological conditions in these areas not only create a shortage of surface water, but are also responsible for the very low permeability of the soils, enriched with highly alkaline and soluble salts, with very low organic content, resulting in poor vegetation,

The requirements of water for drinking for livestock and for irrigation are met either from the ground-water resources or from a network of canals from the neighbouring sub-humid regions, or from the local tanks.

Physiographically, the entire arid zone is characterized by vast tracts, almost covered by a thick blanket of dune sand, except at a few places which are rocky desert. The arid zone has the most unfavourable climatic conditions.

A study of the rainfall map of the north-western Indian arid zone (Sen, 1972) indicates that the region has three rainfall belts, viz. (a) 500 mm to 300 mm, from the foothills of the Aravallis in the east to the desert plains in the west. The zone has typical steppe desert conditions; (b) 300 mm to 100 mm, the hot sandy desert, and (c) below 100 mm, the extremely sandy desert with dunes. The trends of the isohyets are NE to SW.

The area is devoid of any well-defined drainage system, except the Luni River, which has a flood cycle of 16 years. The rest of the drainage lines are mostly internal and ephemeral and carry water only during short cloud bursts and die out soon owing to the alluvial suffocation or excessive evaporation (Sen, 1972). The general slope of the area is towards the south-west. Owing to the internal drainage (Sen, 1972), salt lakes or saline depressions, locally known as *rann*, are common, particularly in the Rajasthan Desert. Prachpadra, Sambhar, Deedwana and Bap are salt lakes. The depressions exist in Sanswarla Ka Rann, Thob, Khatu, Lunkaransar, Pokaran, Kaparda and in the Jaisalmer area of Rajasthan.

The drainage lines of the arid zone of Gujarat are all consequent, having their own local base levels. The drainage lines of the Punjab and Haryana States are in the south-east. The Ghaggar River once flowed through the Ganganagar District (Rajasthan) and drained into the Arabian Sea, after joining the Indus, and is now a 'dry bed' except during rains. The Ghaggar up to 1000 B.C. was known by its more prominent tributary, Saraswati.

GEOLOGY: WATER-BEARING FORMATIONS

The north-western zone of India is considered a shelf, bounded to the south-east by the Aravalli ranges and to the north-west by the Indus plains.

A brief description in relation to the water-bearing formations of the main lithological units is summarized below. The details of the geology are given elsewhere in this publication.

The rocks of the Aravalli system comprise gneisses, schists, phyllites, slates and quartzites, and occur in a part of the Sikar and Nagaur districts. These rocks are hard and crystalline. Ground-water in these rocks moves through joints, fractures, foliation planes and weathered zones. Wells dug to tap these formations yield a poor discharge, ranging from 30 to 60 cubic metres per day.

The Raialo series comprises crystalline limestones with dolomites. Ground-water occurs in joints, fissures and cavities which yield water up to 30 cubic metres per hour.

The rocks of the Delhi system include mica schists, phyllites, calc gneisses and schists and quartzites. Ground-water in these rocks also occurs and moves through the joints, fractures, foliation planes and weathered zones. Wells tapping these formations yield discharges ranging from 40 to 80 cubic metres per day. The Ajabgarhs in the Punjab and in Haryana are fairly good as water-carriers and the wells in them yield discharges ranging from 3.6 to 10 cubic metres per hour (Adyalkar, 1964).

The rocks of Jalore, Siwara, and Erinpura granites, and Malani rhyolites, which are known as the igneous suite of intrusive rocks are very poor aquifers. These rocks yield very limited supplies of ground-water through joints, fractures and weathered zones.

The sandstones and limestones of the Vindhyan age, locally termed the Jodhpur, Bilara and Nagaur group of rocks form good aquifers in these areas. Well tapping these formations are capable of yielding good discharges ranging from 50 to 100 cubic metres per hour.

The Lathi sandstone of Lr. Jurassic age of Jaisalmer is a good aquifer of fresh water. It is capable of yielding high discharge to wells ranging from 100 to 175 cubic metres per hour.

In Kutch, the rocks of Patcham and Chari series comprises calcarious shales and limestone and the quality of water is, therefore, saline. The rocks of the Katrol series are impervious, yielding only a meagre supply of salty water. The Umia series were deposited only under fluviatile and esturine conditions and partly under marine conditions. The marine formation of the series yields only saline water, and, hence, there is no development of ground-water in the fossiliferous sediment of the series. Ground-water in the Bhuj sandstone occurs under both confined and unconfined conditions. The static water level in the dug wells ranges from 2 to 30.5 m.b.g.l. and that in the dug-cum-bore wells and the tube-wells tapping the confined aquifers from 3.4 to 31.4 m. b.g.l. Ground-water to the tune of over 9,000 to 26,000 million litres has been made available for irrigation in the lower and upper Bhuj series respectively in Kutch. The tube-wells located well within the Bhuj sandstones yield about 48.78 cubic metres of water per hour. The quality of water is generally good. In the Deccan traps, in Kutch and in Kathiawar, ground-water occurs along joints, fractures and secondary partings, which are generally limited in depth up to 50 m. The static water level in the dug wells ranges from 4 to 12 m. The yield of wells tapping these formations is moderate.

The semi-consolidated sandstones of the Eocene age and the Alluvial formations of the Quaternary system occupy the major part of the area in western Rajasthan and form good aquifers of potable to brackish water. Wells tapping these formations are capable of yielding good supplies, ranging from 40 to 80 cubic metres per hour.

GROUND-WATER

The ground-water in the arid zone occurs in rocks ranging in age from the Pre-Cambrian to the Quaternary system. In hard crystalline rocks, such as gneisses, schists, phyllites and quartzites, the ground-water occurs and moves through the joints, fractures, foliation planes and weathered zones, whereas in the sedimentary rocks, like sandstones, the ground-water occurs and moves through the porespaces and interstitial openings of granular sediments.

Ground-water in western Rajasthan generally occurs under water-table conditions (unconfined) in hard crystalline and alluvial formations. In sandstones of the Tertiary and older ages, ground-water also occurs under semi-confined to confined conditions owing to the presence of overlying impermeable horizons. The depth up to which water is available in the arid zone ranges from less than 10 m to as high as 140 m below the land surface. The deepest water-table has been observed in the area south of Bikaner in Rajasthan.

At a few places in western Rajasthan, perched water bodies have been observed, and they yield a very limited quantity of fresh water through shallow wells (locally known as 'berries') for drinking. The depths of such bodies range from 8 to 20 metres only, whereas the regional water-table in the area is quite deep.

Table 1. Area (in sq km) under fresh and saline water

District	Total area of the district	Area having fresh water	Area having saline water
Churu	16,261	3,140	13,676
Bikaner	27,102	5,302	21,800
Pali	11,808	9,408	2,400
Jalore	10,428	3,166	7,262
Jaisalmer	38,475	11,797	26,678
Barmer	29,031	7,000	22,031
Nagaur	17,592	12,300	5,292
Jodhpur	22,213	16,213	6,000
Sikar	7,658	7,328	330
Jhunjhunu	5,648	5,443	205
Ganganagar	20,384	1,041	19,343
	2,06,600		1,25,009

THE QUALITY OF GROUND-WATER

The quality of ground-water in western Rajasthan deteriorates along with the decrease in precipitation towards north-west. The saline waters in the arid zone are dominated by sodium and chloride ions. The less saline waters are rich in bicarbonate, sulphate and divalent cations (Paliwal, 1971).

Based on the ground-water investigations, and drillings carried out in the desert areas of Rajasthan, it has been found that the area of about 1,25,009 sq. km has ground-water having chlorides exceeding 1,000 ppm. This area forms about 60% of the total area (2,06,600 sq. km) of western Rajasthan (Table 1).

Table 2. Exploitable ground-water potential in the arid zone of Rajasthan (in mcm)

S. No.	District	Estimated annual re-charge / annual eco-mically mining yield	Existing annual pum-page	Surplus exploitable potential
1.	Barmer	85	40	45
2.	Bikaner	33	10	23
3.	Churu	7	3	4+89*
4.	Sriganganagar	189	75	114
5.	Jaisalmer	930**	8	885**+143+
6.	Jalore	410	200	210
7.	Jhunjhunu	170	96	74
8.	Jodhpur	235	150	85
9.	Nagaur	250	125	125
10.	Pali	330	170	160
11.	Sikar	230	120	110
	Total	1,939	997	950/1,117

* Denotes the economic mining yield in the Churu District.
** Denotes the economic mining yield in the Jaisalmer District.
\+ Denotes the economic mining yield of the Lathi series in the Jaisalmer District.

THE GROUND-WATER RESOURCES

The arid zone of Rajasthan comprises a total area of about 206,600 sq. km and consists of 11 districts. Owing to the poor surface and subsurface drainage, the ground-water in a large part of the area is highly saline and, therefore, cannot be put to any beneficial use. The hydrogeology of the arid region is also very complex and is entirely different from the remaining areas. With a view to locating freshwater aquifers and for assessing their exploitable surplus, systematic studies have been initiated by the Rajasthan Ground-water Department since 1964-65 and by the Central Arid Zone Research Institute since 1962-63. The results of these surveys are being published by these organizations in the form of technical reports and research papers.

The hydrogeological investigations carried out by the Rajasthan Ground-water Department have indicated a large exploitable surplus potential of ground-water in the arid zone of Rajasthan. An account of this potential is given in Table 2 (Mehra, 1976).

The above Table indicates that at present about 50% of the annual recharge is being tapped in the arid districts of Rajasthan, leaving behind 950 mcm of surplus potential and 1,117 mcm of economic mining yield for the districts of Churu and Jaisalmer.

Out of the total area of the arid zone of Rajasthan, 40% of the area contains potable water, whereas in the rest of the area, the quality is saline to highly saline.

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18

THE ARID ZONES OF INDIA: BIO-CLIMATIC AND VEGETATIONAL ASPECTS

V. M. MEHER-HOMJI

ARID zones in their broadest sense may be defined as the zones experiencing chronic water deficit. However, there are large areas in India with water shortage at one time or another. The monsoon regime leaves the major part of the country dry for a period varying from 3 to 11 months on an average, but the inter-yearly variations are quite important and a station experiencing on an average 3 months dryness may be subject to 6 months of dry spell. The mean dryness of 5 months may be prolonged to 8 months, that of 8 months to 11 months, and the zone having 11 months of average dryness may pass a couple of years without a drop of rain (Meher-Homji, 1974a). Whereas the normal dry season, when rains are not expected, goes unnoticed, the extension of the dry spell beyond the time of the onset of the normal rainy season poses a severe threat to water-management and agricultural operations. This is also the case when several weeks pass without receiving any precipitation during the rainy season.

Degree of aridity

Several degrees of aridity may be recognized. *The extremely arid zones are the ones not experiencing any rain for more than a year at a stretch.* Only a very small portion of the extreme western Rajasthân belongs to this category. In other cases, all the 12 months in a year may be dry; there may be a few sporadic showers of very low intensity and duration to characterise any month as humid. Subsequent degrees of decreasing aridity may be recognized on the basis of the number of dry months. Defining a dry month in terms of rainfall poses several problems; the definition of Bagnouls and Gaussen (1953), though empirical, is shown to be of practical use (Meher-Homji, 1963, 1964a). However, the length of a dry period in itself does not convey a true picture of the aridity and the amount of precipitation is also to be taken into consideration. A station, e.g. Bombay, receiving 2,000 mm of rainfall annually has a dry season of 8 months; another e.g. Mysore having a dry season of 4 months may have an annual average of 800 mm of rain only. Therefore Meher-Homji (1962, 1964b) in his index of aridity-humidity proposed the combining of the value of the factor precipitation quantity with that of the length of the dry period. The stations having the values of the index more than 8½ characterize the dry zones.

Another approach that has been followed by Meher-Homji (1972) to define the arid regions is to apply the climatic formulae of several authors.* The stations that are considered to be arid, according to the formulae of all the authors for every individual year, have been classified as *truly arid.* A lower degree of aridity may be granted to the stations turning out to be arid on the average basis as per these formulae, but all the individual years do not fall into the arid category. Further degrees may be recognized on the basis

*These formulae have been discussed earlier (Meher-Homji, 1967).

of a number of formulae classifying the stations as arid, semi-arid or sub-humid. Finally, the climatic regimes** (the season of occurrence of rains) may vary for the stations having the same degree of aridity.

Stability of climate

The climatic data are subject to strong inter-yearly fluctuations, especially in the dry zones (Meher-Homji, 1971 a,b,c, 1972, 1973a). There are variations not only in the amount of rainfall, but also in its duration and regimes. Meher-Homji (1974a) proposed the assessment of climate in terms of a probable year rather than in terms of an average year, as the latter tends to mask the bio-climatic phenomena.

Meher-Homji established the degree of stability of climate of 31 stations of the Indian Sub-continent (Table 1) on the basis of the percentage number of years tallying with the probable year, the latter being defined as the one during which the values of precipitation, rainy days and dry months correspond to the figures of the mean value plus or minus the standard deviation, and the regime is of the commonest type(s). The more stable the climate, the higher is the percentage number of years tallying with the probable year. Only a few individual years agree with the probable year in the case of unstable climate. In Table 1, at one extreme lies Ahmedabad with 65% of the years conforming to the pattern of the probable in all the four factors. At the other extreme is Dera Ismail Khan, with only 8% of the years agreeing with the probable year in which case not only the concept of average year breaks down, but also that of the probable year in view of the small number of years falling within the limits set by the probable type.

Table 1. Degree of stability of 31 stations of the Indian Sub-continent (After Meher-Homji, 1974a)

Station	Percentage No. of years tallying with probable year	Station	Percentage No. of years tallying with probable year
Ahmedabad	65	Gilgit	39*
Peshawar	60*	Dalbandin	39
Sriganganagar	60*	Bombay	38
Sibi	57*	Drosh	38*
Bannu	56*	Kalat	35
Las Bela	56*	Srinagar	33*
Parachinar	49*	Wana	33*
New Delhi	49*	Sukkur	33*
Rawalpindi	48*	Barmer	33*
Sialkot	47*	Lahore	32
Ambala	46*	Nokkundi	31*
Miranshah	44*	Coimbatore	30*
Fort Sandeman	44	Murree	28
Quetta	42	Chitradurga	20
Chaman	41	Dera Ismail Khan	8
Sholapur	40*		

*Probable regime of more than one type

On the recent climatic change

Linked to the variability and stability of the climate is the problem of ascertaining whether the rain in the Indian arid zone is on the wane. This has been a debated subject; the publications appearing till 1963 argued in favour of no climatic change (Pramanik *et al.*, 1952; Rao,

**The regime based on the season of occurrence of rains is either of tropical, Mediterranean, bixeric or irregular type. In the tropical regime, rains are concentrated in summer and in the Mediterranean regime, in winter-spring. The bixeric type is characterized by two dry periods and two rainy seasons in a year. The remaining type without seasonal rhythm is termed irregular.

1958, 1963). However, recently Winstanley (1973) has come out with the theory that since the late 1920s, the summer rainfall in the Sahel zone (south of the Sahara) and in the north-western India has been showing a declining trend, with a corresponding increase in the winter spring precipitation of the Middle East and of regions to the north of the Sahara along the Mediterranean coast. There was a temporary reversal in the 1950s but from 1960s the summer-monsoon rainfall in the Sahel and Rajasthan is once again at a low point of irregular fluctuation with a decreasing trend, whereas the cold-season precipitation of the countries around the Mediterranean Sea is at a high point of an irregular fluctuation with an increasing trend.

One striking point in Winstanley's (*l.c.*) analysis is that he combines the data of different stations, sometimes even of stations having totally different regimes; for example in his Figs. 3 and 5, Marrakeeh, Tunis, Tripoli, Jerusalem, Beirut, Mosul, Shiraz are Mediterranean, having a bulk of the rains in winter-spring, but Atar, Bikaner and Jodhpur are tropical, with rains concentrated in summer.

Using the data of only six stations of the Sahel zone, Winstanley (*l.c.*) worked out an average decrease of 65 mm from 1960 to 1970. Assuming that rainfall in this zone and in Rajasthan would continue to decrease at the same rate as it has done since the late 1920s, he predicts that within the next 55 years, rainfall would be 40 to 45% lower than in the optimum years. He further goes on to generalize that by that time, the Sahara and the Thar deserts will have advanced some 100 km farther south.

In view of the fact that only two Indian stations, Jodhpur and Bikaner, were considered in the above study and their data were not analysed individually, Legris and Meher-Homji (1976) investigated the trend of precipitation of 13 Indian stations from a bio-climatological point of view.

Inter-yearly variations have been noticed in the total and seasonal rainfall and in the rainy days. The character of raininess is assessed by using two parameters: (1) the amount of rainfall, and (2) the number of rainy days. It may happen that the quantity of rainfall may fluctuate widely from year to year, without there being any considerable change in the number of rainy days. On the other hand, the decrease in precipitation may be closely linked with the number of days when it rains. The third possibility is that the rainfall may become too concentrated, a few rainy days giving a high total.

If the quantity of rainfall seems a delicate parameter to appreciate from a bio-climatological view point, the number of rainy days could be equally tricky. In the meteorological archives, just 2 mm of rain suffices to make a rainy day. Of what agro-climatic use could be such a low quantity in the tropics, with high temperatures and especially if preceded and followed by long spells of drought? We may assign equal weightage both to the amount of rainfall and the number of rainy days.

Besides the total rainfall and the number of rainy days, due consideration has to be given to the seasons. As it is pertinent to know the trends during the main cropping period, two seasons are considered: (1) the relatively warm period (May–October) coinciding with the prevalence of the south-westerly monsoon over the greater part of the peninsula, and (2) the relatively cool winter-spring season (November–April). In the northern and north-western parts of the Subcontinent, the western disturbances bring rains during this cool season.

The trends of increasing or diminishing rainfall and the rainy days for eight stations are presented in Table 2 after Legris and Meher-Homji (1976).

Of the eight stations, Sriganganagar, New Delhi and Sholapur show an increasing tendency in the total rainfall, whereas Ambala, Barmer, Ahmedabad, Chitradurga and Coimbatore present a decreasing trend.

In the case of Ambala, though the total rainfall is on the decline, the rainfall of the main rainy season, i.e. May–October with 84% of the total rainfall, shows an

Table 2. Trends of increase or decrease in the total and seasonal rainfall and the rainy days of 8 Indian dry-zone stations according to 20-year moving averages

Station and years	Trends of rainfall			Trends of no. of rainy days		
	Total	May to October	November to April	Total	May to October	November to April
Sriganganagar (1937–1969)	Increase (+2 to +10%) since 1948*	Increase (+2 to 13%) since 1948 (83%)**	Decrease (—4 to —5%) since 1958 (17%)	Increase (+2 to +12%) since 1946	Increase (+1 to +13%) since 1947 (74%)	Increase (+3 to +8%) since 1958 (26%)
Sholapur(1927–1973)	Increase (+2 to +13%) since 1947	Increase (+2 to 15%) since 1946 (92%)	Decrease (—7 to —36%) since 1944 (8%)	Increase (+1 to +7%) since 1945	Increase (+1 to +8%) since 1946 (91%)	Decrease (—1%) since 1963 (9%)
New Delhi (1891–1970)	Increase (+2 to +14%) since 1948	Increase (+2 to +17%) since 1948 (88%)	Decrease (—2 to —19%) since 1950 (12%)	Decrease (—1%) since 1959	Increase (+2 to +10%) since 1948 (81%)	Decrease (—3 to —27%) since 1936 (19%)
Chitradurga (1927–1970)	Decrease (—1 to —4%) since 1949	Average in 1959,1960. Decrease (—1%) in 1957,1958. (84%)	Decrease (—5 to —14%) since 1949 (16%)	Decrease (—1 to —3%) since 1957	Average in 1959,1960 Decrease (—1 to —2%) (85%) in 1957,1958	Decrease (—4 to —10%) since 1954 (15%)
Ambala (1927–1970)	Decrease (—1 to —4%) since 1955	Increase (+1%) since 1960 (84%)	Decrease (—2 to —12%) since 1952 (16%)	Decrease (—2 to —3%) since 1957	Decrease (—1 to —2%) since 1957 (76%)	Decrease (—1 to—11%) since 1952 (24%)
Coimbatore (1927–1970)	Decrease (—2 to —4%) since 1956	Decrease (—1 to —5%) since 1954 (60%)	Increase (+2%) since 1960 (40%)	Decrease (—2 to —3%) since 1956	Decrease (—1 to —3%) since 1956 (63%)	Decrease (—1 to —5%) since 1956 (37%)
Barmer (1932–1970)	Decrease (—3 to —8%) since 1958	Decrease (—1 to —7%) since 1958 (93%)	Decrease (—4 to —46%) since 1945 (7%)	Decrease (—1%) since 1959	Increase (+1 to +19%) since 1941 (91%)	Decrease (—10 to —50%) since 1945 (9%)
Ahmedabad (1927–1973)	Decrease (—2 to —5%) since 1954	Decrease (—1 to —4%) since 1955 (98%)	Decrease (—13 to —20%) since 1958 (2%)	Decrease (—1 to —5%) since 1955	Increase (+1 to +2%) since 1961 (93%)	Decrease (—4 to —8%) since 1958 (7%)

*The year mentioned after "since" refers to the central year in the 20-year average.
**Contribution of the seasonal rainfall and rainy days to the total is given in the second bracket.

increase of 1% since 1960. On the other hand, the dry season, i.e., November-April, registers a fall in the rainfall at Sholapur and New Delhi where the total and the May-October rains show an increase. The contribution of this dry season to the total rainfall is only 8 to 12%.

If the total number of rainy days is taken into consideration, New Delhi, Chitradurga, Ambala, Coimbatore, Barmer, and Ahmedabad present a waning trend and Sriganganagar and Sholapur an increasing tendency.

However, New Delhi, Barmer and Ahmedabad present an increasing trend in the number of rainy days of the principal rainy season, i.e. May-October, with over 80% of the rainy days concentrated in this period. Chitradurga presents an average trend.

No geographic correlation is noticed between the increasing trend and the decreasing trend. Even two neighbouring stations may show an opposing tendency as in the case of Barmer (the total rainfall having decreased since 1958) and Sriganganagar (with an increasing trend since 1948).

The trends may be illustrated with a few examples. Figs. 1 and 2 show the variability in the seasonal rainfall and the rainy days in respect of New Delhi and Barmer. The yearly fluctuations as well as the curves of the 5-year and the 20-year running means are presented. The strong inter-yearly variations may be noticed both in respect of the rainfall and the rainy days. The 5-year moving means likewise fluctuate between the surplus rainfall and the deficit rainfall at irregular intervals. In Figs. 1a, 1b, the 20-year moving average curves show the general upward trend of the total and the May-October rainfall and the rainy days at New Delhi. Figs. 1c and 1d outline the diminishing trend for the November-April rainfall and the rainy days. Figs. 2a to 2d show the declining trends at Barmer, with reference to the 20-year averages, though in the case of the May-October rainy days, the values remain on the positive side (Fig. 2b).

It may be noticed from Table 2 that out of the six parameters (rainfall and the rainy days, the total and of the two seasons), Sriganganagar presents decreasing trend only in the November-April rainfall. Sholapur is marked by decreases in two parameters—the November-April rainfall and the rainy days. Bearing in mind that this is the statistically dry season, the trend is not significant from the agro-meteorological angle. New Delhi presents decreases in three parameters viz., in the November-April rainfall and rainy days, and in the total number of rainy days. Chitradurga maintains an average tendency only in May-October; the total and the November-April rainfall and rainy days register decreases. Ambala, Coimbatore, Barmer, and Ahmedabad show the increasing trend in one parameter only, i.e., that pertaining to rainfall in respect of the first two stations, and to the May-October rainy days in respect of the remaining two. *Thus no station shows an out-and-out increasing or decreasing tendency.*

In conclusion, whereas it would not be correct to say that India has become drier in the recent years, the population explosion and the attendant water needs for domestic and agricultural purposes has increased the human dependence on the weather so much that the low-rainfall years weigh heavily on the economy.

Recently, Raman (1974) has prepared a monsoon map of Maharashtra, emphasizing the sowing dates for various agro-climatic regions, bearing in mind the variability in the commencement of the monsoon. Legris *et al.* (1971) analysed the daily rainfall records of several years of the drought-prone Anantapur region of Andhra Pradesh and recommended that the sowing of paddy should be done in the second half of July when rains become reliable, rather than with the first rains in June or May which are followed by days without effective rains. Fast-growing varieties could amply make up for the delay in sowing.

Given the variability of the climatic

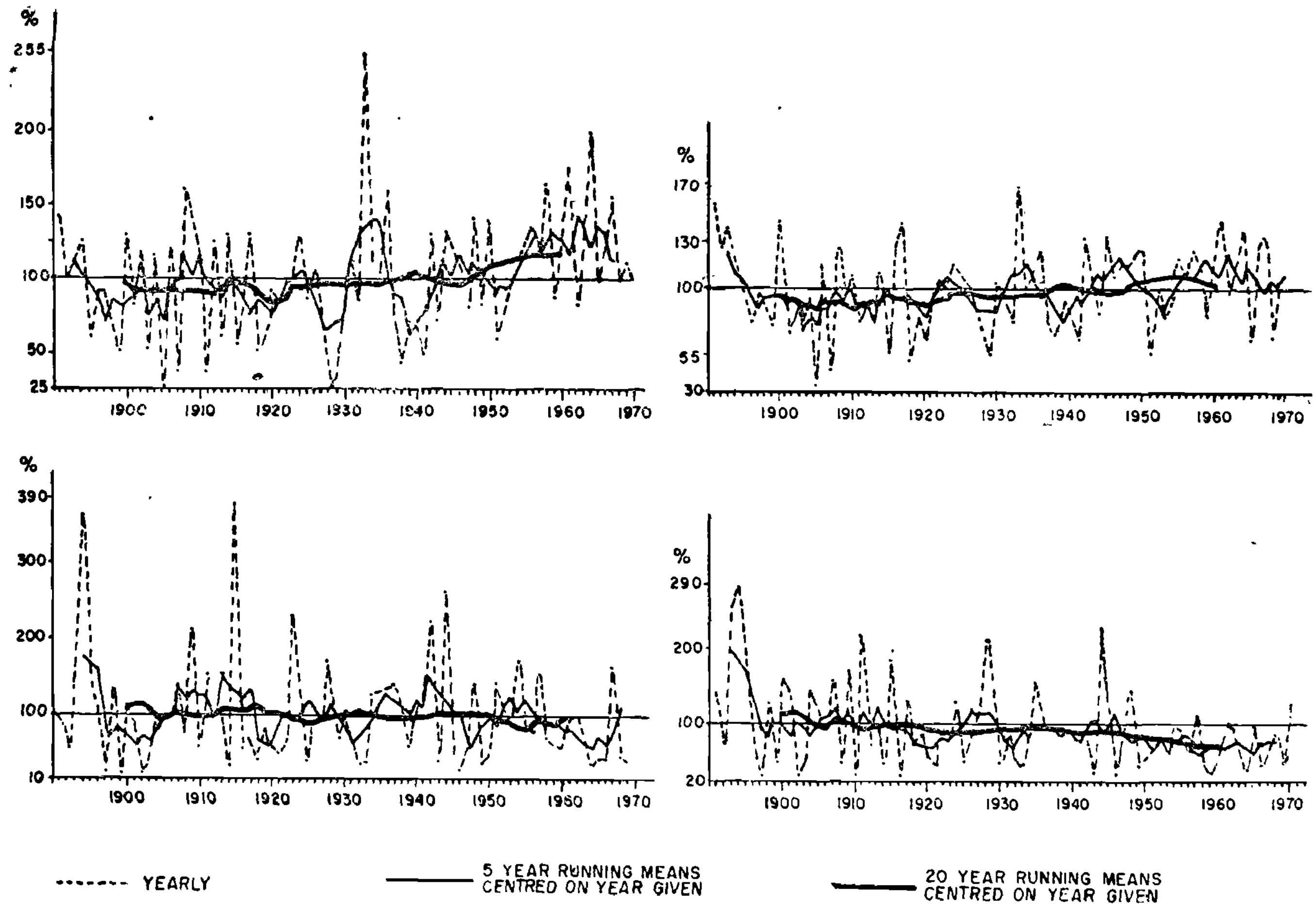

Fig. 1a (Top left) New Delhi—Rainfall for the period May-Oct.
Fig. 1c (Bottom left) New Delhi—Rainfall for the period Nov.-April

Fig. 1b (Top right) New Delhi—Number of rainy days for the period May-Oct.
Fig. 1d (Bottom right) New Delhi—Number of rainy days for the period Nov.-April

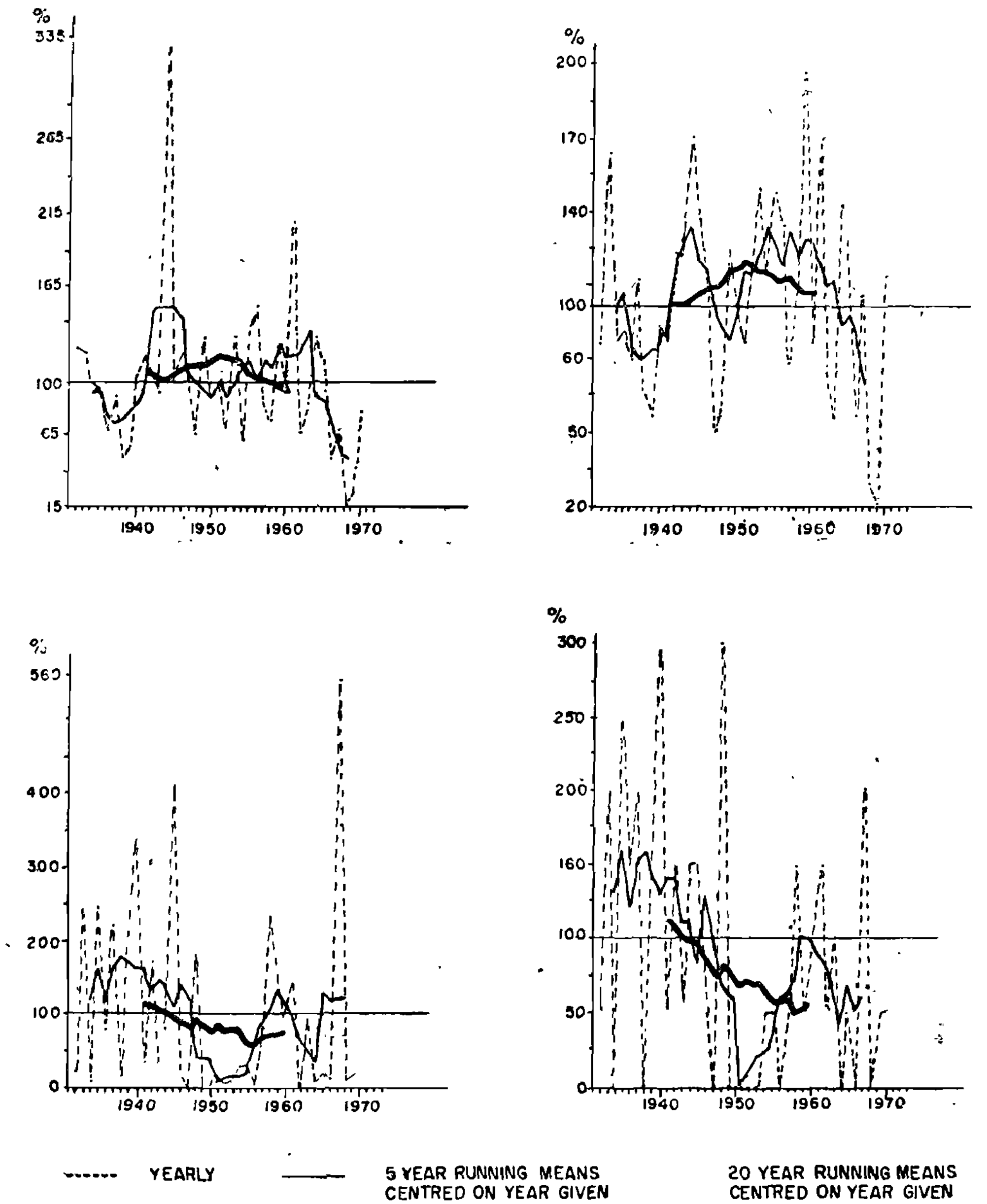

Fig. 2a (Top left) Barmer—Rainfall for the period May–Oct.

Fig. 2b (Top right) Barmer—Number of rainy days fo⁻ the period May–Oct.

Fig. 2c (Bottom left) Barmer—Rainfall for the period Nov.–April.

Fig. 2d (Bottom right) Barmer—Number of rainy days for the period Nov.–April.

factors, another logical approach would be to delimit the bio-climatic zones purely on the basis of the natural vegetation. The plant-cover is a good reflector of the environmental conditions and also integrates the variability aspect of the climate.

Further, the regions derived from vegetational criteria point out the various land-units having a certain ecological uniformity and a particular degree of aridity*.

Vegetation types and their controlling factors

The physiognomic aspect of the desert is poor, scanty, xerophytic vegetation, widely dispersed, leaving large areas bare. The sub-deserts comprise steppes or thorn-forests. Whereas the steppe is an expression of the cold-sub-desertic climates, the thorn-forest is the rule under hot but equally dry regions.

The following vegetation types of India may be listed under the category "arid" in its broadest sense in the decreasing order of aridity: (1) *Calligonum polygonoides*; (2) *Prosopis cineraria-Capparis decidua-Zizyphus-Salvadora*; (3) *Acacia-Capparis decidua*; (4) *Acacia senegal-Anogeissus pendula* and (5) *Acacia catechu—Anogeissus pendula*. The arid zone in the classical sense would include only the first two types, viz. *Calligonum*, and *Prosopis-Capparis-Zizyphus-Salvadora*. The type *Acacia-Capparis* would characterize the semi-arid zones of Rajasthan, northern Gujarat and the Deccan. The *Acacia planifrons* type (the southern umbrella thorn forest of Champion, 1936) and the *Acacia-Anogeissus pendula* types of the Aravallis would also be included in the typical semi-arid class.

Some other types, such as *Anogeissus pendula - Anogeissus latifolia, Albizzia amara, A. amara - Anogeissus latifolia, A. latifolia* and *Hardwickia binata*, which do not include teak and mostly fringe the semi-arid *Acacia - Capparis* community may be included under the marginally sub-dry category as they grow under conditions less favourable than the sub-humid belt where the teak (*Tectona grandis* L.f.) makes its appearance. The optimum physiognomic state which these types reach, is a forest but under the pressure of a high density of human and cattle-goats population the woodlands often degenerate into thickets and savannas and such formations are frequently subject to water stress.

I. Calligonum polygonoides type**

The most arid parts of western Rajasthan and Pakistan are characterized by the community of *Calligonum polygonoides* L. which physiognomically occurs in the shape of scattered shrubs. It is encountered mostly on sand-dunes and sometimes also on loose sands. The annual average rainfall is less than 400 mm and the length of the dry season exceeds 9 months.

The characteristic species of this type, besides *C. polygonoides* itself, are *Leptadenia pyrotechnica* (Forsk.) Decne., *Haloxylon salicornicum* Bunge ex Boiss., *Cyperus arenarius* Retz., *Rhynchosia arenaria* Blatt. *et* Hallb. and *Dipterygium glaucum* Decne.

Whereas *C. polygonoides* is confined to the dune slopes, *H. salicornicum* is commoner in the inter-dunal areas and besides occurs in the north-western part of Rajasthan where rainfall is exceedingly low (200 mm, with 11 months dry).

L. pyrotechnica requires a gravelly subsoil. Together with, another Asclepiadaceae, *Sarcostemma acidum* (Roxb.) Voigt, it forms a degradation stage of *Calligonum*.

Among the common species may be mentioned *Aerva persica* (Burm. f.) Merr., *A. pseudotomentosa* Blatt. et Hallb., *Panicum turgidum* Forsk., *Calotropis procera* R.Br., *Crotalaria burhia* Buch.-Ham., *Indigofera cordifolia* Heyne ex Roth. *I. argentea* L. and *Tephrosia falciformis* Ramasw.

The following species are occasionally encountered in the *Calligonum* community: *Cleome pipillosa* Steud., *Citrullus colocynthis* Schrad., *Gisekia pharnaceoides* L., *Ephedra foliata* Boiss., *Aristida mutabilis* Trin. et Rupr., *Cenchrus biflorus* Roxb., *C. ciliaris* L., *C. prieurii* (Kunth)

*Meher-Homji (1975) has used species-area floristic statistics in combination with climatic characters to give a better indication of the bio-climatic degrees of aridity-humidity than the climatic data alone.

**The description of vegetation is after Gaussen, Meher-Homji *et al.* (1972) and Gaussen, Legris *et al.* (1968a).

Maire, *Dactyloctenium aegyptiacum* (L.) Beauv., *D. sindicum* Boiss., *Lasiurus hirsutus* (Forsk.) Boiss, *Eragrostis ciliaris* (L.) R.Br., *E. tremula* Hochst., *Panicum antidotale* Retz., *Saccharum bengalense* Retz., *Leucas aspera* Link., *Indigofera linifolia* Retz., *Lycium barbarum* L., *Tribulus alatus* Del., *T. terrestris* L.

On the low dunes are found *Acacia jacquemontii* Benth., *Leptadenia pyrotechnica*, *Aerva persica*, *Balanites aegyptiaca* (L.) Del., *Lycium barbarum*, *Capparis decidua* (Forsk.) Pax and *Calotropis procera*, but only the first two species are very conspicuous. Sand-dunes are usually cultivated with *bajra* (*Pennisetum typhoides* (Burm.) Stapf *et* Hubb.), but in the eastern part of the Jaipur District, even wheat is grown on fixed dunes in terraces. In the less drier areas, such as parts of Churu, Bikaner, Nagaur and Sikar districts, the dunes have been fixed by afforestation and they support thickets of *Prosopis cineraria* (L.) Druce, *Zizyphus nummularia* W.*et* A., *Z. mauritiana* Lam. *Acacia spirocarpa* Hochst. ex A. Rich. var. *tortilis*, an exotic, has given good results in fixing some protected dunes near Bikaner and Jhunjhunu.

II. Prosopis cineraria-Capparis decidua-Zizyphus-Salvadora type

The range of rainfall is 150 to 400 mm, with 9 to 11 months dry. The mean temperature of the coldest month ranges from 10° to 20°C. From the edaphic point of view, the type is mainly confined to the old alluvial sandy soils.

The type is found in the Barmer, Bikaner, Jaisalmer, Jodhpur, Nagaur districts and in the western parts of Jalore and Pali districts of Rajasthan and also in Kutch.

The human interference in this arid belt has obliterated almost completely the natural vegetation and only traces of it are left in protected places such as the *orans* which are the areas dedicated to the local deities. Usually the *orans* occur on the outskirts of the villages. The best stands are in the form of thorny thickets, but they are of rare occurrence. More commonly encountered are discontinuous thickets, shrub-savannas and scattered shrubs.

In the *orans* of the southern part of western Rajasthan, the main species are *Prosopis cineraria*, *Capparis decidua*, *Salvadora oleoides* Decne.; *Zizyphus nummularia* W.*et* A. is better represented in the northern parts (the Bikaner, Churu districts) where winter temperatures are lower. Other elements encountered in the discontinuous thicket are *Acacia nilotica* (L.) Del., *Salvadora persica* L., *Zizyphus mauritiana*, *Balanites aegyptiaca*, *Lycium barbarum*, L. *europaeum*, *Calotropis procera*, *Aerva persica*, *A. pseudotomentosa*, *Crotalaria burhia*, *Ephedra foliata* Boiss., *Tephrosia purpurea* Pers., and *Saccharum bengalense*.

Prosopis juliflora DC. is also occasionnally encountered in the southern parts of Rajasthan. In the northern regions it suffers because of the low temperature. *P. cineraria* is a light demander. Sensitive to frost and drought in juvenile stage, the older plants resist these adverse conditions. It prefers loose sandy soils, tolerates moderately sandy soils but avoids heavier, clayey soils. It is rare around Nagaur where the soils are of a red gravelly type; because of the lack of soil depth on the exposed *kankar* pan, its growth is not favoured. However, if the calcite concretions (*kankar*) lie at a depth of 70 to 80 cm, the growth of *P. cineraria* is favoured because these concretions leave a large number of sand-filled pockets that trap the infiltrating water. Blagoveschenskiy (1968) has traced a correlation among the height and density of *P. cineraria*, the underneath grass-cover and the climatic characters. In the north-eastern part of Rajasthan, around Jaipur, with 500–600 mm of rainfall *Prosopis* trees are 7 to 8 m high, with a density of 150–200 per hectare. The height of the herbage under the trees is 100–120 cm, with a predominance of tall grasses of the Andropogonae tribe. In the central part around Ajmer, the annual precipitation is of the order of 300–400 mm. Here, *Prosopis*-trees are 5 to 6 m tall, 50 to 100 per hectare. The grass cover is 50-60 cm high and almost all the tall grasses (*Lasiurus hirsutus* (Forsk.) Boiss., *Desmostachya bipinnata* (L.) Stapf. are preserved, but are reduced in height and numbers. Low xerophytic members of the tribe Agrostidae (mainly the genus *Aristida*) begin to play a significant role in the composition of the herbage. In the west around Phalodi, the annual precipitation is reduced to about 200 mm; the density of *P. cineraria* of 3 to 4 m in height is 25–30 per hectare. *Aristida* spp. dominate among the grasses. The representatives of Andropogonae, especially *Lasiurus*, are present but are not dominant.

Capparis decidua is generally absent from sand-dunes and deep loose sandy soils, but tolerates the moderately sandy texture. It prefers loamy or clayey soils, is common in river valleys, comes up even on gravelly soils and is found in higher numbers in areas which have a *kankar* pan underneath. It may occur in low-lying areas and depressions where the soil is either derived from rock or is heavy. The example of the first type is observed between Phulera and Jaipur and of the second type between Sardarshahr and Bikaner.

When sand overlies a lime or gypsum bed, the dominant elements of the vegetation are *Calotropis procera*, *Aerva persica* and *A. pseudotomentosa* serving as indicators of these minerals. Gillet (1968) has described *C. procera* as an *anthropophilous nitratophilous* psammophyte of Ennedi Massif (Sahara) where it comes up on the sites that were once the camps of the nomads and invades impoverished fields, ruined lands and sandy soils. In Rajasthan, it behaves as a psammophyte and anthropophilous plant as it grows on sandy soils, sand-dunes and has a tendency to come up on the sites disturbed by man, including the areas mined for gypsum. The nitratophilous nature is not as strongly exhibited by *C. procera* as its vicarious species *C. gigantea* Br. of the more humid parts of India. In Rajasthan, *C. procera* is related to the calcium content of the soil.

Salvadora oleoides occurs on heavier and somewhat saline soils. In the older alluvial plains, it is a co-dominant element with *Prosopis cineraria* (Gupta and Saxena, 1968). *S. persica* L. is grown in compounds and hedges because of its economic importance. Its fruits produce an oil used for burning in lamps; the fruits are also fed to cattle to increase the fat content of their milk. It occurs in areas that are slightly saline, but the salinity is subterranean.

Acacia jacquemontii is seen along the sides of the rivers but is also encountered on hillside dunes dissected by water channels. *Zizyphus nummularia* is conspicuous in northern Rajasthan where temperatures are lower. It needs sandy to sandy-loam soil. According to Satyanarayan (1964), *Z. nummularia* is a seral stage leading to the climax of *Prosopis cineraria-Salvadora oleoides*. Given the good development of *Zizyphus* in the northern region, the species deserves the status of plesioclimax (Sensu Gaussen, 1959).

The convergence of growth forms in *Capparis decidua*, *Calligonum polygonoides*, *Leptadenia pyrotechnica*, *Ephedra foliata*, *Crotalaria burhia* is noteworthy.

In the shrub-savanna physiognomy, some shrubs are left standing amidst grasses. These grazing-lands are locally known as *birs*. Among the shrubs, *Prosopis cineraria* is common. Others are *Capparis decidua*, *Zizyphus nummularia*, *Lycium europaeum*, *Maytenus emarginata* (Willd.) Ding Hou, *Acacia nilotica* (L.) Del., *Z. Jaquemontii*, *A. leucophloea*, *Leptadenia pyrotechnica*, *Sericostoma pauciflorum* Stocks, *Aerva persica*, *Crotalaria burhia*.

The grasses under protection reach a height of 75 cm to 1m in the rainy season. The common grasses are *Aristida adscensionis* L., *A. funiculata* Trin. *et* Rupr., *Cenchrus biflorus*, *C. setigerus* Vahl, *C. ciliaris*, *Cymbopogon jwarancusa* (Jones) Schult, *Dactyloctenium aegyptiacum*, *D. sindicum*, *Dichanthium annulatum* (Forsk.) Stapf, *Digitaria adscendens* (Hk.) Henr., *Eragrostis ciliaris*, *E. tremula*, *Eleusine compressa* (Forsk.) Aschers. *et*

Schweinf., *Eremopogon foveolatus* (Dal.) Stapf., *Melanocenchris jacquemontii* Jaub. *et* Spach. In the northern and western regions, *Lasiurus sindicus* Henr. is important. Closure favours palatable grasses, such as *Cenchrus ciliaris*.

The effect of controlled grazing on the grass-cover in the Jodhpur District is demonstrated by Das and Bhimaya (1964). Annuals in the initial stages constituted 71% with *Aristida funiculata* and *A. adscensionis* jointly contributing 55%. After three years of controlled grazing, the percentage of perennial grasses, such as *Eleusine compressa, Cenchrus ciliaris, C. setigerus* and *Eremopogon foveolatus* increased by almost 13% over the initial index.

After the termination of the rainy season, an acute dearth of fodder is felt; the nomads with their herds set out eastwards. There is heavy pressure on the grazing-lands and only the unpalatable scattered shrubs are left. Tree species, e.g. *Prosopis cineraria* and *Salvadora oleoides*, are lopped during the lean periods.

Acacia senegal Willd. and *Maytenus emarginata* grow on rocky soil or on rocks covered by sand. They are the indicators of a rocky substratum covered by sand. *Fagonia cretica* L. tolerates lime and gypsum. *Tithonia rotundifolia* (Mill.) Blake is an exotic, now spreading in Rajasthan. *Mukia maderaspatana* M. Roem. is a climber seen quite frequently on *Capparis decidua*; *Citrullus colocynthis* Schrad. is a trailer. *Saccharum bengalense* is found in the northern and north-eastern parts into which it has been introduced. Blagoveschenskiy (1968) has used this species to name the type *Prosopis-Saccharum* in his map. In view of its introduced nature, the validity of the type is questionable. Besides, *S. bengalense* occurs only in the fields or hedges.

On gravelly soils, the following scattered undershrubs and herbs are encountered: *Barleria acanthoides* Vahl, *Boerhaavia diffusa* L., *B. verticillata* Poir., *Bonamia latifolia* (Hochst. *et* Steud.) Sant., *Cleome papillosa* Steud., *Corbichonia decumbens* (Forsk.) Exell, *Fagonia cretica, Indigofera enneaphylla* L., *I. linifolia* Retz., *I. trigonelloides* Jaub. *et* Spach, *Leptadenia pyrotechnica, Salvia aegyptiaca* L.

III. Acacia-Capparis type

This type which physiognomically occurs in the shape of a thicket, scattered shrubs or shrub savanna characterizes the semi-arid regions. In Rajasthan, it occurs in the piedmont plains west of the Aravallis in Sirohi, Jalore and Pali districts; the altitudinal range varies from 150 to 300 m. In Gujarat, the type is encountered in the western parts of the Broach and Baroda districts, the Kaira, Ahmedabad, Mehsana districts and almost the whole of Kathiawar peninsula, excluding the hilly regions above 300-m altitude. In Maharashtra, it covers the dry interior Deccan area throughout its entire length from the south of Dhulia to the south of Miraj. It extends but very little in northern Karnataka, the limit of the type tallying fairly well with the Deccan Trap geological formation to the south of Miraj, Bijapur and Gulbarga, the geology changes from the Trap to gneissic complex shale, sandstone, quartzite and chlorite schist and the *Acacia-Capparis decidua* type is replaced by *Albizzia amara*. In Madhya Pradesh, this series occupies a limited area near Barwani, north-west of Khargon.

From the edaphic point of view, the type occurs on several soils, viz. black soils on alluvia or on the Trap, red ferruginous soils and alluvial soils. *Albizzia amara*, an acidophilous species, on the other hand, cannot tolerate black clayey calcimorphic soils and is thus eliminated from the Deccan Trap country. The range of rainfall is 400 to 700 mm, with 8 to 9 months dry.

Floristically, the differences between this type and the preceding one in Rajasthan and northern Gujarat are mainly quantitative. Almost all the important species of the *Acacia-Capparis* type, such as *Acacia nilotica*, *A. leucophloea* Willd., *Capparis decidua, Commiphora mukul* (Hook. ex Stocks) Engl., *Euphorbia caducifolia* Haines, *Zizyphus* spp., are present in the *Prosopis-Capparis-Zizyphus Salvadora* type, where *Prosopis cineraria, Salvadora oleoides, Zizyphus nummularia* also are better represented. Certain species, such as *Acacia jacquemontii, Cordia gharaf* (Forsk.) Ehr. *et* Asch., *Tecomella undulata* (Smith) Seem, *Leptadenia pyrotechnica, Aerva persica, Crotalaria burhia*, are preferential of *Prosopis-Capparis-Zizyphus* type, whereas *Cassia auriculata* L. is confined to the *Acacia-Capparis* type.

Other shrubby species are *Alhagi camelorum* Fisch., *Balanites aegyptiaca* (L.) Del., *Clerodendrum phlomidis* L.f, *Dichrostachya cinerea* W. & A., *Flacourtia indica* (Burm. f.) Merr., *Grewia tenax* (Forsk.) Fiori, *Grewia villosa* Willd., *Lycium europaeum* L., *Taverniera nummularia* DC., *Xeromphis spinosa* (Thunb.) Keay.

In the Deccan, *Euphorbia nerifolia* on the trap is a geographic vicariant of *E. caducifolia* of Rajasthan-Kathiawar.

Acacia planifrons W. & A. of the Porbandar region of Kathiawar also occurs in the semi-arid south-eastern corner of India near Tuticorin and Pamban in the Tirunelveli and Ramanathapuram districts and in a few localities in the Madurai and Coimbatore districts of Tamil Nadu. It is found also in Bellary, but it is planted there. Morphologically, the species is closely allied to *Acacia spirocarpa* Hochst. ex A. Rich. of North-East Africa and Arabia. The important trade of horses in the past via the sea route between Arabia, Africa and the ancient ports of India may explain the disjunct distribution (Viart, 1963; Meher-Homji, 1970).

IV-V. Acacia senegal-Anogeissus pendula type and Acacia catechu-Anogeissus pendula type

The hills of the Aravalli range and other hillocks protruding in the Thar are characterized by a vegetation of their own. *Anogeissus pendula* Edgew. is the most remarkable species of the Aravallis. In the comparatively dry tract (rainfall : 400–700 mm; 8½–10 months dry), it is usually associated with *Acacia senegal*, but in the more humid parts of Eastern Rajasthan (rainfall : 550–900 mm; 8-9 months dry), *Acacia catechu* Willd. is the vicarious species. The two types, *Acacia senegal—Anogeissus pendula* and *Acacia catechu—Anogeissus pendula*, are closely allied having many species in common. However, the latter is richer in species at least in the forest stage.

Acacia senegal—Anogeissus pendula type has its largest extension in the Sirohi, Pali, Ajmer, Jaipur and Sikar districts, though it also occurs on the isolated hills and hillocks of the Jalore, Barmer, Jodhpur and Nagaur districts. The type is associated mainly with brown soils.

Acacia catechu—Anogeissus pendula type is developed mostly in the eastern districts: Alwar, Sawai Madhopur, Tonk, Bundi, Morena, Kota, Bhilwara, Chittaurgarh and Shahjapur. It is also found on the Aravalli range in the Sirohi, Pali and Ajmer districts. The soils are of brown and black types under this type. The altitudinal range of the type in the Pali, Sirohi and Udaipur districts is about 500 m, above which it makes room for the *Anogeissus latifolia-Terminalia* forest.

Acacia leucophloea dominates in the piedmont zone.

Dry deciduous low forest

The dry deciduous low forest consists of four tiers, viz;

(*i*) The emergent tree layer
(ii) The small trees forming an understorey
(iii) The undergrowth of shrubs and climbers
(iv) The ground cover of herbs and grasses.

Top storey

The average height of the trees in the top canopy is 10 m. *Anogeissus pendula* is the dominant species, mostly forming almost pure stands.

Though the tree seeds profusely, the germination of the seeds is very poor. What is seen as profuse natural crop of seedlings in the forest is actually the profuse reproduction by the root suckers.

Species common in the top canopy of

the forests of both the types are: *Acacia leucophloea*, *Butea monosperma* (Lam.) Taub. (at the foot hills), *Bauhinia racemosa* Lam., *Holoptelea integrifolia* Planch., *Moringa concanensis* Nimmo, *Wrightia tinctoria* R.Br., *Mitragyna parvifolia* (Roxb.) Korth. (along the streams), *Boswellia serrata* Roxb., *Lannea coromandelica* (Houtt.) Merr., *Sterculia urens* Roxb., *Diospyros melanoxylon* Roxb., *Albizzia odoratissima* Benth. (on the upper slopes and crests of the hills).

Deciduous species, such as *Aegle marmelos* Corr., *Bombax ceiba* L., *Dalbergia paniculata* Roxb., *Cassia fistula* L., *Soymida febrifuga* Juss., *Crataeva religiosa* Forst. f., *Feronia limonia* (L.) Swingle, *Anogeissus latifolia* Wall., and the evergreen species of more moist sites (e.g. Ranthambor Hill, Sawai Madhopur Dist.) like *Syzygium cumini* (L.) Skeels, *Mangifera indica* L., *Mallotus philippensis* Muell. Arg. occur occasionally in the *Acacia catechu-Anogeissus pendula* type.

The understorey is about 6 m in height, with an average density of 0.3. It is composed of :

Dichrostachya cinerea
Zizyphus mauritiana Lam.
Balanites aegyptiaca (L.) Del
Maytenus emarginata
Cordia gharaf and the bamboo
Dendrocalamus strictus Nees.

Flacourtia indica, *Zizyphus glaberrima* Sant., *Zizyphus xylopyrus* Willd., *Nyctanthes arbortristis* L., *Helicteres isora* L., *Xeromphis spinosa*, *Holarrhena antidysenterica* Wall. occur exclusively in the *Acacia catechu-Anogeissus pendula* type.

The undergrowth is about 2 m high, comprising

Grewia flavescens Juss.
Grewia tenax
Rhus mysorensis Heyne
Commiphora mukul

Mimosa rubicaulis Lam.
Securinega virosa (Roxb. ex Willd.) Pax et Hoffm.
Zizyphus nummularia
Adhatoda vasica Nees.

Euphorbia caducifolia and *Dyerophytum indicum* Kuntze are encountered on the rocky sites.

Among those encountered only in the *Acacia catechu-Anogeissus pendula* type are *Capparis spinosa* L., *C. zeylanica* L., *Ehretia laevis* Roxb., *Clerodendrum phlomidis*, *Securinega obovata* Muell. Arg. and *Euphorbia nivulia* Buch-Ham., the last-mentioned in the rocky habitat.

Climbers and twiners, common to both the types, include *Abrus precatorius* L., *Cocculus pendulus* (Forst.) Diels, *Cuscuta reflexa* Roxb. and *Asparagus dumosus* Baker. There are some more seen only in the *Acacia catechu-Anogeissus pendula* type; *Asparagus racemosus* Willd., *Tinospora cordifolia* Miers, *Mucuna prurita* Hook., *Ichnocarpus frutescens* R. Br., *Hemidesmus indicus* R.Br.

Ground-cover is composed of herbs, such as *Cassia tora* L., *Borreria hispida* (L.) Schum. and *Tridax procumbens*. Wherever there are openings, the ground is covered with grasses such as *Apluda mutica* L., *Aristida hystrix* L.f., *Eremopogon foveolatus*, *Heteropogon contortus* (L.) Beauv., *Melanocenchris jacquemontii* Jaub. *et* Spach, *Chrysopogon fulvus* (Spreng.) Chiov. *Riparian facies*: Along the nalas occur *Ficus glomerata* Roxb., *Phoenix sylvestris* Roxb., *Syzygium jambos* (L.) Alst., *Mitragyna parvifolia*, *Soymida febrifuga*. *Ficus glomerata* is affected by frost. In the Sariska Game Sanctuary (Alwar District), frost occurs in the first fortnight of December. On an average, there are 3 frosty days in December.

The thorny thicket

This is a degraded stage of the low forest. The general height of the crop is 3 to 4 m. This formation resembles the *Acacia-Capparis* and the *Prosopis-Capparis-Zizyphus* types in floristic composition.

Species typical of these two dry types, such as *Aerva persica*, *Prosopis cineraria*, *Capparis decidua*, *Sericostoma pauciflorum*, are present in the thickets of the *Acacia senegal—Anogeissus pendula* type and the *Acacia catechu—Anogeissus pendula* type; *Acacia jacquemontii*, *Calotropis procera*, *Capparis decidua*, *Cassia auriculata*, *Leptadenia pyrotechnica*, *Lycium europaeum* occur in the thickets of the *Acacia senegal—Anogeissus pendula* type only.

However, the presence of *Anogeissus pendula*, *Grewia tenax*, *G. flavescens*, *Flacourtia indica*, *Rhus mysorensis*, *Securinega virosa*, *Capparis sepiaria* L., *Cassia tora* in these thickets indicate a higher status—the potentiality to evolve towards the *Acacia-Anogeissus pendula* type on further protection.

Euphorbia caducifolia, *Zizyphus nummularia*, *Zizyphus mauritiana*, *Balanites aegyptiaca* are also represented.

Bushes of *Anogeissus pendula* are heavily browsed and are hardly 1 m tall. When protection is better, it is about 2 m high.

Acacia senegal and *Maytenus emarginata* are indicators of rocky substratum (the occurrence of bed rock at a shallow depth). When the rocks and even entire hillocks are buried under the sand, they point out their presence

Some thickets are invaded by *Prosopis juliflora.*

Discontinuous thicket

This is the next stage of degradation where the regeneration, both coppice and seed, is not allowed to come up because of continual browsing and grazing. The site conditions have also deteriorated owing to soil erosion.

Anogeissus pendula is cut recklessly and is so badly browsed that it almost touches the ground. The spreading of such bushes is almost 2 m in diameter.

Euphorbia caducifolia and *Rhus mysorensis* are two common shrubs. Among the others, mention may be made of *Acacia leucophloea*, *A. senegal*, *A. catechu*, *Dichrostachys cinerea*, *Balanites aegyptiaca*, *Maytenus emarginata*, *Zizyphus nummularia*, *Dyerophytum indicum*, *Adhatoda vasica*, *Grewia* spp. The ground flora is very sparse.

Shrub-savanna

Certain areas, known locally as *jors* or *birs* (grass reserves), are earmarked for the production of grass and for grazing. They are interspersed with cultivation. Shrubs about 3 to 4 m in height are scattered amidst grass-cover attaining a height of 1 m and even more during the rains. Herbs are very few.

VI. The marginal sub-dry vegetation types

Among the marginal vegetation types, indicating the sub-dry zones, *Albizzia amara* type occurs mostly in the Coromandel—Circar plains of Tamil Nadu and Andhra Pradesh. The most striking feature of the climate is the tropical dissymmetric regime. The rains are light during July–September, but heavy in October–November, mainly from the depressions originating in the Bay of Bengal during the N.E. monsoon season (Meher-Homji, 1973b, 1974b). The rainfall within the belt of *Albizzia amara* varies from 600 mm to 1,500 mm. The variability is also quite large, depending on the frequency of the depressions. The length of the dry season ranges from 6 to 8 months. The thickets and scrub-woodlands of *Albizzia amara* are confined to ferruginous, ferrallitic or skeletal soils.

In the transitional zone where the rainfall regime changes from the dissymmetric type to the true tropical type (with rains from May-June to October), the *Albizzia amara-Anogeissus latifolia* community occurs as an *ecotone*. A good example is seen in the Mysore-Hunsur tract (Meher-Homji, 1977a).

Generally, teak (*Tectona grandis*) disappears from the dry deciduous forests of the regions of low rainfall, usually less than 750 mm, with the dry season exceeding 8 months (as in northern Gujarat, Rajasthan and the Deccan). The resultant community is termed *Anogeissus latifolia* type. Teak, as a rule, also disappears from the forests adjoining the *sal* (*Shorea robusta* Gaertn.) type, though rainfall is more than 750 mm; rarely do teak and sal occur together in a "tension" belt. The dry deciduous miscellaneous forests without teak or sal of central India are also classified in the *Anogeissus latifolia* type.

In parts of the Udaipur, Sirohi, Pali,

Ajmer and Kota districts of Rajasthan, two species of *Anogeissus—A. pendula* and *A. latifolia* overlap each other. The rainfall in this tract is of the order of 600 to 800 mm, with a dry season of 8 months.

Finally, it remains to make a mention of the *Hardwickia binata* type of dry deciduous forest which has a very wide range of rainfall (500 to 1,200 mm, spread over 4 to 6 months) and soil types (from hard gravelly to deep black clayey). The disjunct patchy distribution of this type has been explained on the basis of anthropogenic interference (Meher-Homji, 1970, 1977b).

One may well question the placing of the forests and other arborescent formations of these marginal types under the arid category. However, when such wooded areas are degraded by man and his domesticated animals, they get converted into low thickets, scattered shrubs or overgrazed grasslands and often become drought-prone.

Summary and conclusion

The present paper reviews some of the approaches to define the degrees of aridity from a bio-climatic viewpoint. It also highlights the variability in the amount of rainfall, its duration and seasonal distribution and points out the need of delineating a probable year rather than an average year, taking into consideration the instability of the climates of the dry belts. The waning trend of precipitation proposed for the Indian arid zone has not been supported by the 20-year moving averages. The natural vegetation which integrates the variability aspect of the climate provides convenient guidelines for delimiting the arid (with *Calligonum* and *Prosopis—Capparis—Zizyphus Salvadora* types), the semi-arid (*Acacia—Capparis* and *Acacia—Anogeissus pendula* types) and the marginal sub-dry zones (*Albizzia amara*; *Anogeissus latifolia* and *Hardwickia binata* types). In the last category, it is mainly through excessive anthropogenic interference that the terrain turns drought-prone. Those areas of peninsular India having good forest formations or those containing teak or sal may be excluded from the arid or semi-arid category; a probable exception may be the *Acacia-Anogeissus pendula* forests of the Aravallis, but these are, in fact low or open formations. The paper terminates with a discussion on physiognomy, flora and main climate and soil factors of the vegetation types of the dry zones.

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19

VEGETATION AND ITS SUCCESSION IN THE INDIAN DESERT

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VEGETATION is a part of the complex ecosystem which includes the plant cover, the landform and the features of its surface deposits. In a desert, a close relationship exists among the habitat, the vegetation and its environment. This relationship of an arid zone is always in a dynamic equilibrium. Minor changes in the physical environment entail dynamic changes in plant life. The vegetation differs in the sequence of species (landform and surface deposits) and varies in sequence of time as well (seasonal and year-to-year). The dynamic rhythm of plant life varies in magnitude as one passes from the extremely arid region (100–150 mm) of rainfall of the western part of Jaisalmer to the eastern part of Rajasthan (200–750 mm) and beyond. Within the same environmental conditions, the sharp changes in topographical features, there is a distinct delimitation of the plant community (stand). The present communication deals with the vegetation types on different landforms under various bioclimatic zones. Emphasis has been laid on the potential vegetation, the existing status, the extent of degradation and the possible successional trends.

Blatter and Halberg (1918–1921) recognized five formations from western Rajasthan. Champion (1936) classified the vegetation into four main types which were later reclassified into eight forest types of Champion and Seth (1964). Mathur (1960), however, described six forest types only. Bharadwaj (1961) distinguished three primary and six secondary landform regions. Gaussen *et al.* (1971) classified the vegetation of the region into twelve types, constituting three formations. In an account of the ecology of the Jodhpur Tehsil, Shantisarup and Vyas (1957) have recognized six plant associations according to different "situations". Saxena (1972) recognized seven ecosystems in western Rajasthan and the description of the vegetation was based on the five formations recognized by Satyanarayan (1963). Gupta (1975) enlisted six formations which had a little enlargement of the vegetation types classified by Satyanarayan (1963). In the present investigation, six formations have been recognized, with a slight modification of the classification made by Satyanarayan (1963) and Gupta (1975). These are (A) the mixed xeromorphic thorn forest, (B) the mixed xeromorphic woodland, (C) the mixed xeromorphic riverine thorn forest, (D) the lithophytic scrub desert, (E) the psammophytic scrub desert, and (F) the halophytic scrub desert.

VEGETATION TYPES

(A) Mixed xeromorphic thorn forest

Besides the Aravallis as the boundary line, there are several rugged hills scattered in western Rajasthan. They are mostly of sandstone, granite and rhyolite. The plant communities growing on these hills are grouped under the 'mixed xeromorphic thorn forest' because the communities are largely dominated by thorny and spiny species, which include some evergreen non-thorny species as well. Here, the soils are skeletal, yellowish brown to brown loamy sands. Low hills and rocky regions falling in a zone of 150 to 300 mm of rainfall are largely dominated by the *Acacia senegal* community under due protection with a density of 72 plants per ha and 100% frequency. The *Anogeissus pendula-Acacia senegal* community covers a rainfall zone of 350–500 mm, whereas in the zone of 500–750 mm and above, the *Anogeissus pendula* community predominates. Here, *Acacia catechu* becomes the chief associate, but on higher elevations *A. pendula* combines with *Boswellia serrata*. The plant density ranges from 200 to 500 plants per ha, with 15–35 cm DBH.

(i) In the low-rainfall zone (150–250 mm), *A. senegal* forms a low layer of 3-4 m in height and the trees are sparsely distributed, with 5–12 per cent crown cover. The associated shrubs and trees are short, with crooked boles and include *Salvadora oleoides* and *Maytenus emarginatus*. The chief shrub associates in this rainfall zone are *Commiphora wightii*, *Zizyphus nummularia*, *Grewia tenax*, *Euphorbia caducifolia*, *Mimosa hamata* and *Sericostemma acidum*. Their density varies from 85–540 per ha. The aboveground biomass contributed by these species ranges from 18.5 to 45.5 q per ha. The associates of *A. senegal* community in the medium (250–350 mm)-rainfall zones include *Wrightia tinctoria*, *Moringa concanensis*, *Azadirachta indica*, *Bauhinia racemosa*, *Cordia gharaf*, *A. leucophloea*. In the higher-rainfall regions (300–700 mm), some more species are found, e.g. *Securinega leucopyrus*, *Dichrostachya cinerea*, *Grewia villosa*, *Barleria prionites*, *B. acanthoides*, *Cassia auriculata*, *Abutilon indicum* and *Dipteracanthus patulus*, which had 8–18 per cent crown cover and 115–750 plants per ha constituting 47.5 q per ha above-ground biomass. The ground flora in the low-rainfall zone is also quite poor and includes a few species of grasses and forbs, such as *Cymbopogon jwarancusa*, *Aristida funiculata*, *Eleusine compressa*, *A. hirtigluma*, *Tragus biflorus*, *Oropetium thomaeum*, *Melanocenchris jacquemontii*, *Enneapogon brachystachys*, *Indigofera cordifolia*, *I. linnei*, *Lepidagathis trinervis*, *Blepharis sindica*, *Tephrosia purpurea* and *Tridax procumbens*. All these species come up during the monsoon and impart a light-green hue to the landscape. In the higher-rainfall zone (350–750 mm), some more species, besides the above mentioned ones, viz. *Eremopogon foveolatus*, *Heteropogon contortus*, *Brachiaria ramosa*, *Bothriochloa pertusa*, *Hackelochloa granularis*, *Sehima nervosum*, *Indigofera tinctoria*, *Tephrosia petrosa*, *Boerhavia diffusa*, *Pupalia lappacea* and *Achyranthus aspera*, are quite prevalent. The hilly areas under low rainfall are generally dominated by *Eleusine compressa-Aristida* sp. community, whereas in the higher-rainfall zone, the optimum expression is given by the *Sehima nervosum* community, contributing 11.5% ground cover and 46.7 q per ha above-ground biomass. Several intermediate communities of other grasses are encountered in the hilly tracts.

The majority of the hillocks possess degraded vegetation owing to severe lopping and cutting by man and owing to grazing by large herds of animals. One can encounter cut and coppiced stamps of *A. pendula* which assume a cushioned, crawling structure, whereas *A. senegal*, rarely coppices and gives bushy appearance. Degraded seral communities are represented by *Euphorbia caducifolia* and *Cassia auriculata* in shrub layers, whereas *Lepidagathis trinervis-Oropetium thomaeum* community covers the ground. *Euphorbia* contributes about 5% of the crown cover, with 16.0 q per ha of above-ground biomass, *O. thomaeum* produces almost a negligible biomass (0.14 q/ha).

(B) Mixed xeromorphic woodlands

This formation is largely constituted by spiny species mixed with non-spiny and evergreen species or with those species having stems and branches or both green. It occurs on the flat older alluvial plains and lower piedmont plains, with deep soil depositions. Here, the soils are deep, sandy loam, loamy, sandy clay loam and clay with a hard *kankar* pan at varying depths (25 cm–100 cm). The type of in-duration (Indurated and semi-indurated) differences in the depth of the soil are well expressed by the plant community and its overall performance. The natural vegetation of the plains is highly modified owing to cultivation. In general, the climatic climax of the Indian Thar Desert is represented by *Prosopis cineraria* and *Salvadora oleoides* community, which is distributed throughout the plains of western Rajasthan. *P. cineraria* has a wider ecological amplitude and its optimum density (150-200 per ha) and vigour can be seen in the districts of Sikar, Churu and Nagaur (300-400 mm). Its density decreases on both sides of this rainfall zone. Various degraded stages of this formation are met all over the plains of western Rajasthan. The representative vegetation is as follows :

1. *Salvadora oleoides-Prosopis cineraria* are generally recorded on the lower piedmont plains, which are covered with a very deep sand deposition in a zone of 300-400 mm rainfall. *S. oleoides* occurs both in tree and shrub forms. Other associated trees and shrubs are *Maytenus emarginatus*, *Acacia leucophloea*, *Z. nummularia*, *C. decidua*, *Euphorbia caducifolia*, *Grewia tenax* and *Balanites aegyptiaca*. The plant density ranges from 180-215 plants per ha, with 8-10 per cent crown cover which contributes 30-35 q per ha of the above-ground biomass. The same plant community on flat older alluvial plains, with deep heavy soil, produces as high as 146.0 q/ha of the above-ground biomass, with 17.6% crown cover.

2. *Prosopis cineraria-Zizyphus nummularia-Capparis decidua* community is most prevalent on a large part of the flat plains. Because of the year-to-year cutting, *Z. nummularia* plants do not show any visible impact on the cultivated fields whereas this species plays a dominant role in the shallow soils of the low-rainfall zone (150-300 mm). On an average, there are 15-20 plants per ha of *Prosopis*. They grow to a height of 10-14 m, with 50-80 cm of girth at breast height. In a cultivated field, 90% dominance is indicated by *Prosopis*. In a *beer* or *oran* (the common village grazing-land), the plant density of the community ranges from 150-390 with 4.8 to 17.76 per cent crown cover. Such a community yields 18.5 to 75.6 q per ha of above-ground biomass. Under degraded conditions, there is an increase of shrub density (347 per ha), but less of crown cover (6.7%).

Other plant communities encountered in the desert plains are (3) *Salvadora oleoides-Capparis decidua-P. cineraria*, (4) *Salvadora oleoides*; (5) *Capparis decidua-S. oleoides*, *P. cineraria*, (6) *S. oleoides-C. decidua*, (7) *P. cineraria-S. oleoides-Z. nummularia*, (8) *S. oleoides-Cassia auriculata*, (9) *P. cineraria-C. decidua*, (10) *P. cineraria-Z. nummularia*, (11) *C. decidua*, (12) *Zizyphys nummularia*, (13) *S. oleoides-P. cineraria-Z. nummularia*, (14) *P. cineraria-Acacia nilotica*.

The above plant communities by the inclusion or exclusion of anyone species affect the association significantly. Therefore these may be regarded as phases "facies" of the climax community and indicate the extent of degradation. The absence of all the above 4-5 species represent severely degraded stages, shown by *Tephrosia purpurea*, *Crotalaria burhia* and *Indigofera oblongifolia* with 2.5-3.5% crown cover and 6.2 to 8.6 q per ha of the above-ground biomass.

The common shrub associates of all the above communities include *Calotropis procera*, *Balanites aegyptiaca* and *A. jacquemontii*. The forbs and grasses are *Aerva persica*, *Tephrosia purpurea*, *Crotalaria burhia*, *Convolvulus microphyllus*, *Heliotropium subulatum*, *Pulicaria wightiana*, *Celosia argentea*; *Eleusine compressa*, *Dactyloctenium sindicum*, *Desmostachya bipinnata*, *Cenchrus ciliaris*, *C. setigerus*. The maximum expression of *Cenchrus* type of grassland has 18.7% basal cover, with 34.6 q per ha of the above-ground biomass. The values under severe degradation get reduced to 1.5% cover and 9.35 q/ha of the above-ground biomass.

(C) Mixed xeromorphic riverine thorn forest

The Jawai, the Sukri, the Mitri and the

Luni rivers and their tributaries in western Rajasthan form a narrow belt of younger alluvium on both sides of their courses. These areas are liable to inundation. The soils have heterogeneous deposits comprising sand, silt and gravel and form deep sandy soils without a hard pan. The lands are almost flat, but at certain places, hummock formations are encountered along the banks. Enough underground water, sweet to brackish, is available at shallower depths. Numerous wells are dug for irrigated *rabi* crops. Invariably, there is a very good density and growth of a few species, e.g. *Acacia nilotica, A. nilotica* ssp. *cupressiformis, Salvadora oleoides, S. persica* and *Tamarix articulata, Tecomella undulata.* Around the wells, the farmers maintain a few trees, e.g. *Azadirachta indica, Tamarindus indica, Albizzia lebbek, Ailanthus excelsa, Ficus religiosa, F. bengalensis, Moringa oleifera* and *Zizyphus mauritiana.* These trees provide shade and top-feed material for the livestock.

Acacia nilotica-Prosopis cineraria community is most prevalent on irrigated fields along the river course and the climatic climax of this region. There are generally 25-45 plants per ha with the height averaging 7-10 m and 25-40 cm diameter at breast height. *Acacia* has a high regeneration capacity in these soils, but owing to cultivation, the density of the trees is always under control. A density of 68 per ha makes up 12.4 per cent crown cover and produces 47.7 q/ha of the above-ground biomass on sandy-loam soils. Whereas on medium heavy soils, *S. oleoides* and *P. cineraria* dominate, with 52 plants per ha in shrubby form bearing only 7.5% crown cover and 17.5 q per ha of the above-ground biomass. Degradation beyond this stage is quite rapid and species, e.g. *Tamarix, Zizyphus, A. jacquemontii,* flourish for a short spell and they dwindle sharply under severe biotic stress which finally leaves the grass community of *Desmostachya bipinnata-Cyperus arenarius* and *C. biflorus,* producing 2.5 q per ha of the above-ground biomass and 3-4% ground cover.

Other plant communities on the terraces of the river banks are: (i) *Acacia jacquemontii-Cassia auriculata,* (ii) *A. jacquemontii-Aerva pseudotomentosa,* both on hummocky terraces, (iii) *Salvadora persica-Tamarix articulata,* (iv) *Salvadora oleoides-C. decidua.* These communities represent the disclimax and are represented by shrub species (1-3 m in height). They produce 5-11% crown cover and 5.7-14.5 q per ha of the above-ground biomass.

The grasses and forbs under these communities are *Cenchrus ciliaris, C. setigerus, Aristida adscensionis, Digitaria adscendens, Dactyloctenium aegyptium, Chloris virgata, Cynodon, Tephrosia purpurea, Solanum surattense, Vernonia cinerascens, Heliotropium subulatum, Crotalaria burhia, Boerhavia diffusa, Digera muricata, Pulicaria wightiana, Voluterella divaricata, Xanthium strumarium, Kylinga* sp., *Launea* sp. and *Indigofera cordifolia.*

(D) Lithophytic scrub desert

Eroded rocky surfaces, gravelly plains and pediment plains of sandstones, limestone, granite, quartzite, slate, etc. are scattered in the districts of Jodhpur, Nagaur, Jaisalmer and Barmer. These plains serve as upland to the adjoining flat plains. They are covered with gravel and rock fragments of various sizes and are subject to water erosion. The soil cover is very shallow. Soil deposition takes place in depressional pockets and folds where stunted, multi-branched shrub and tree species form cushion-shaped structures. They are largely utilized as grazing-lands and are covered with "scrub desert" vegetation.

Capparis decidua community

It is the most prevalent shrub community of eroded rocky surfaces and piedmont plains. Here, the community is quite open, with a low density (5-25 plants per ha) and very poor growth (3-5 q per ha of the above-ground biomass) due to skeletal soil cover. Stray plants of *Acacia senegal* and *Prosopis cineraria,* 2-3 m in height, can also be seen along the deep tunnels. Associated shrubs, undershrub, forbs and grasses are:

(i) *Leptadenia pyrotechnica, Calotropis procera, Zizyphus nummularia,* (ii) *Aerva persica, Tephrosia purpurea, Crotalaria burhia, Sericostemma pauciflorum, Bonamia latifolia, Tribulus terrestris, Orygia decumbens,* (iii) *Cleome papillosa, C. brachycarpa, Boerhavia elegans, B. diffusa, Mollugo cerviana, Indigofera cordifolia, Salvia aegyptiaca,* (iv) *Dactyloctenium sindicum, Oropetium thomaeum, Eleusine compressa, Eragrostis* sp., *Aristida hirtigluma.*

Zizyphus nummularia-C.decidua community.

The gravelly plains where sheet wash has resulted in exposing the *kankar* pan (i.e. from Nal to Kolayat in the Bikaner District) are dominated by this community. The shrubs are fairly numerous, being 80–120 per ha, especially in those spots where reaccumulation of sand has taken place up to 50 cm. Here, the community grows to a height of 1.5 to 3 m, with 6–8% crown cover and 25–35 q/ha of the above-ground biomass in a partially protected site (Gajner). It represents the stable disclimax of this habitat. But once more, the soil accumulation takes place, it may lead to the climax community of *Prosopis cineraria.*

(E) Psammophytic scrub desert

This formation has woody vegetation predominantly of shrubs, 1–3.5 m in height. They are mostly localized on aeolian deposits, i.e. on stabilized sand-dunes and undulating hummocky older alluvial plains and inter-dunal hummocky plains. Here, soils are very deep loamy sands and are calcareous. The fresh sand deposition and the subsequent colonization is well depicted by typical psammophillous species, namely *Aerva persica, A. pseudotomentosa, Crotalaria burhia, Panicum turgidum, Cyperus laevigatus, Calligonum polygonoides, Clerodendron phlomoides, Cenchrus biflorus, Aristida funiculata, Citrullus colocynthis.*

Sand-dunes are extensive in western Rajasthan and occupy approximately 50% (Pandey *et al.*, 1964) of the total area. So far, five types of sand-dunes, namely parabolic, longitudinal, transverse, barchan and shrub-coppice dunes (Saxena and Singh, 1976) have been recognized in western Rajasthan. The first type of dunes are a few prominent centres of dune concentration and they make the indistinct provinces. These dunes have been recorded in higher concentration in each province. They are generally closely spaced and get coalesced owing to the action of cross winds. Several coalesced dunes at the leeward end present a shape of zigzag transverse dunes. In-between the chains of parabolic dunes, longitudinal dunes are generally formed in the same axial direction. The sand of these stabilized dunes is quite compact and calcareous. In some cases, lime nodules, 1 cm to 10 cm in size, have been recorded on the dune flank and windward side. Stabilized dunes whose flanks and crest have fresh sand deposition, 1–5 m in depth, mostly bear shrub vegetation with a few distantly scattered trees, whereas the sand-dunes free from fresh sand deposition are invariably occupied by more trees and a few shrubs only. There is a gradual change in the vegetation of the stabilized dunes from the low-rainfall zone (100–200 mm) to the higher-rainfall zone (350–500 mm).

Dune vegetation in the much-lower-rainfall zone (100–200 mm) is quite scanty with a limited number of species. In this tract, the longitudinal, parabolic and transverse dunes are very high (30–60 m) which are largely dominated by "psammophytic" species. These dunes are recorded to be in highly disturbed conditions. Continuous droughts, together with biota, have aggravated sand erosion which has resulted in deposition of a large amount of loose sand on the crest and flank of these dunes. In some cases, the flanks of longitudinal and parabolic dunes are covered by chains of barchan dunes. Such dunes have skeleton vegetation on the surface. Spaces left between the barchan dunes are occupied by *Aerva pseudotomentosa, Indigofera argentea, Crotalaria burhia, Dipterygium sp. Citrullus colocynthis, Panicum, turgidum,* *Cenchrus biflorus*, *Aristida funiculata*, *Eragrostis* sp., *Tephrosia falciformis*, *Rhynchosia minima* var. *memnonia* and stray shrubs of *Calligonum polygonoides*, *Calotropis procera*, *Haloxylon salicornicum* and *Acacia jacquemontii*. Sand-dunes with their active crest and leeward end have the following communities: (a) *Calligonum polygonoides-Panicum turgidum*, (b) *Acacia jacquemontii-Calligonum polygonoides*, (c) *Calligonum polygonoides-Haloxylon salicornicum-P. turgidum*.

The above species are well distributed over the lower and upper flanks and windward side of the dunes indicating comparatively loose layer of sand over them. Highly disturbed dunes have very low productivity (1–2 q/ha), and plant density (20–60 plants per ha), whereas the moderately effected dunes, on an average, bear 3–5% crown cover. The plant density varies from 70–210 plants per ha which put up 5 q/ha of the above-ground biomass.

The three stabilized dunes in the low-rainfall zone (200–250 mm) are comparatively much compact, except for their crest and leeward end. A few dunes under severe biotic stress have a similar fate as in the lower-rainfall zone. The formation of barchan dunes on flat land and on stabilized parabolic dunes can be seen near big settlements, e.g. Phalodi. In this zone, all the three types of dunes are cultivated for *kharif* crops right from the lower slopes of the flanks to the crest. Sand-dunes with moderate sand deposition are found with the following communities:

(1) *Calligonum polygonoides-Clerodendron phlomoides*, (2) *C. polygonoides-Panicum turgidum*, (3) *Acacia jacquemontii-Acacia senegal*, (4) *Maytenus emarginatus-Calotropis procera*, (5) *M. emarginatus-A. senegal*, (6) *A. senegal-Calligonum polygonoides*. (7) *Crotalaria burhia-Aerva pseudotomentosa*, (8). *C. burhia-Sericostemma pauciflorum-Leptadenia pyrotechnica*.

Continued cultivation on dune slope reduces the shrub species. Few trees can be seen on the lower and middle slopes of the dune flanks and in some cases on the stabilized leeward face. In this zone *A senegal* comes up very well on all dune aspects indicating the extent of stabilization.

Common associates of the above plant communities on different aspects of the dunes are:

(i) *Dune crest*: *Panicum turgidum*, *Cymbopogon jwarancusa*, *Panicum antidotale*, *Aerva pseudotomentosa*, *Citrullus colocynthis*, *Cyperus laevigatus*, *Farsetia hamiltonii*, *Crotalaria burhia*, *A. funiculata*, *C. biflorus*.

(ii) *Leeward side*: *Calotropis procera*, *Aerva pseudotomentosa*, *Calligonum polygonoides*.

(iii) *Dune flanks*: (*x*) *Upper slopes*: *Clerodendron phlomoides*, *Acacia jacquemontii*, *Maytenus emarginatus*, *Calotropis procera*, *Lasiurus sindicus*, *Citrullus calocynthis*, *Eragrostis* sp., *Cyperus bulbosus*, *Crotalaria burhia*, *C. biflorus*, (y) *Dune bases and lower slopes*: *Prosopis cineraria*, *Tecomella undulata*, *Leptadenia pyrotechnica*, *Lasiurus sindicus*, *Aerva persica*, *Indigofera cordifolia*, *I. trigonelloides*, *Polycarpea corymbosa*, *C. ciliaris*, *C. biflorus*, *Aristida funiculata*, and *Cymbopogon jwarancusa*.

Some of the dunes have partial protected conditions under religious bindings where grazing by large herds of animals is permitted, whereas cutting and lopping are almost restricted. These dunes develop into a small forest of *Acacia senegal-Maytenus emarginatus*. It had 10–14% crown cover, with 200–310 plants per ha. The estimated above-ground biomass ranges from 30–42 q per ha. Dunes with a similar community but under cultivation have only 5% crown cover and 5.7 to 14.9 q/ha of the above-ground biomass. The absence of *C. polygonoides* and *Clerodendron phlomoides* from such dunes also indicates the compactness of the topmost sand. Most of the Shergarh dunes (Jodhpur District) are highly stabilized and do not show any sand-piling. Such dunes mostly bear tree and shrub species of the alluvial plains.

The same dunes in the moderate-rainfall zone (250–300 mm) are more stabilized and bear a larger number of small trees and a few shrub species, such as *Prosopis cineraria*, *Salvadora oleoides*, *Balanites aegyp-*

tiaca, Tecomella undulata, Maytenus emarginatus, Lycium barbarum and *Acacia jacquemontii.* The occurrence of trees on various aspects of dunes indicates the stabilization over a considerable period of time (La Touche, 1902). The trees and shrubs are widely scattered and do not form a plant community. But some of the dunes under a long duration of protection support distinct communities, e.g. (1) *Acacia senegal-Maytenus,* (2) *Maytenus emarginatus-Lycium barbarum-A. senegal,* (3) *C. polygonoides-Prosopis cineraria-Saccharum bengalense.* Regular cultivation on the stabilized dunes restricts the growth of shrub species, whereas distantly spaced trees are allowed to grow. A protected dune has 10–18% crown cover, 150–350 plants per ha, producing 60–90 q per ha of the above-ground biomass. Whereas these figures get reduced to 3–4% crown cover, 60–110 plants per ha and 10–21 q per ha of the above-ground biomass on the periodically cultivated dunes. The forage species of the ground flora on these dunes include *Lasiurus sindicus, Cenchrus ciliaris, Cymbopogon schoenanthus, C. jwarancusa, Panicum turgidum, C. biflorus, Aristida mutabilis, Indigofera cordifolia, I. linifolia, Crotalaria burhia, Farsetia hamiltonii* and *Saccharum bengalense.* The production of above-ground biomass from these species varies from 14–26 q per ha, with 8.0–9.9% basal cover (Chohtan-Barmer).

The sand-dunes in a higher-rainfall zone (300–400 mm) are highly stabilized and support "mixed xeromorphic woodland" instead of psammophytic scrub desert. A good number of *Prosopis* trees (40–60/ha) form a definite plant community. The trees grow right from the base to the top of the dune. The trees are well spaced all along the upper slopes. These dunes are comparatively low (20–40 m). Almost all the aspects are put under cultivation. This practice leads to sand erosion which contributes to the formation of new dunes and hummocks, etc. *Saccharum bengalense,* once introduced into the area of these dunes, helps to conserve the soils on these cultivated or uncultivated dunes to a great extent. Shrub species e.g. *Leptadenia pyrotechnica, Calotropis procera, Mimosa hamata, Lycium barbarum, C. decidua* and *Z. nummularia* are concentrated on the upper ridges of the longitudinal dunes. This shrub line takes the shape of a hedge separating the two fields. The ground species include *Tephrosia purpurea, Saccharum spontaneum, Crotalaria burhia, Aerva persica* and *I. falciformis.*

Sandy undulating hummocky plains and inter-dunal plains are formed through aeolian action, owing to which the sand has been deposited in the form of sand sheets or hummocks, colonized by psammophyllous species. e.g. *Calligonum polygonoides, Aërva pseudotomentosa, Leptadenia pyrotechnica, Acacia jacquemontii,* forming cushion-shaped bushes. Interspaces between the mounds are occupied by *Lasiurus sindicus, Cymbopogon jwarancusa, Tephrosia purpurea* and *Crotalaria burhia* and *Citrullus colocynthis.* In the 100–200 mm-rainfall zone, *Haloxylon salicornicum* is the prevalent species, whereas in the higher-rainfall (200–350 mm) zone, *Zizyphus nummularia* is common. Sparsely scattered trees of *Tecomella undulata, Prosopis cineraria* and *Salvadora oleoides* are present throughout this terrain. In the district of Barmer, Bikaner, Jaisalmer and Jodhpur the following shrub communities are listed:

(1) *Calligonum polygonoides-Haloxylon salicornicum;* (2) *C. polygonoides-Leptadenia pyrotechnica;* (3) *C. polygonoides-Zizyphus nummularia;* (4) *C. polygonoides-Lasiurus sindicus;* (5) *C. polygonoides-Acacia jacquemontii;* (6) *Calotropis procera-Aerva pseudotomentosa;* (7) *Acacia jacquemontii-A. pseudotomentosa;* (8) *Crotalaria burhia-A. pseudotomentosa-Leptadenia pyrotechnica;* and (9) *Mimosa hamata-Clerodendron phlomoides.*

These species are good soil-binders but grazing, cutting and the revival of these practices results in wind erosion. A shrub community of *Calligonum* and *A. jacquemontii* with 302 plants per ha, produces 55 q per ha of the above-ground biomass, occupying 9% crown cover. The degradation of this intermediate stage reduces the crown cover to 3.3 per cent and 6.7 q per ha of the above-ground biomass. The *Prosopis-Tecomella* community or the *Prosopis-Balanites* community has, on an average, 30 plants per ha, bearing 18.5% crown cover, whereas the above-ground biomass is as high as 64.7 q per hectare.

(F) Halophytic scrub desert

This formation is characteristic of the arid areas. It is generally localized in low-lying saline basin and depressional areas. The saline basins are almost level, with 1% slope. The runoff water from the surrounding areas brings silt and clay, along with fine sand, which gets deposited in thin layers. Here the soils are heavy clay loam to clay, deep and highly saline. The water stagnates for a few days to a few months. The surface layer on drying is covered with a white crust of salt in the form of patches which remain almost devoid of vegetation. Malhar, Sanwarla, Thob, Pokaran, Pachpadra, Uterlai, Lawana, Loonkaransar, Kharia, and Mitha Rann of Jaisalmer are worth mentioning from western Rajasthan.

In the Rann (*playa*), the salinity decreases towards the periphery where succulent halophytic nano-phanerophytes and chaemophytes, generally of Chenopodiaceae, Zygophyllaceae, Aizoaceae and Portulacaceae are prevalent. The plants of these families get a foothold on the spots where some sand deposition has taken place or the salinity level is low.

The plant communities recorded on various ranns are:

(1) *Suaeda fruticosa-Aeluropus lagopoides* (Sanwarla-Pachpadra, Malhar); (2) *Haloxylon salicornicum-Salsola baryosma-Sporobolus marginatus* (Malhar, Khari Rann); (3) *Sporobolus helvolus-Cyperus rotundus* (Thob); (4) *Peganum harmala-Eleusine compressa-Sporobolus marginatus* (Jamsar, Lunkaransar, Nal); (5) *Desmostachya bipinnata-Eleusine compressa* (Uterlai).

Other halophytic species common to the above communities are: *Haloxylon recurvum, Zygophyllum simplex, Cressa cretica. Euphorbia granulata, Portulaca oleracea. Fagonia cretica, Salsola baryosma, Trianthema portulacastrum, Echinochloa colonum, Chloris virgata, Schoenfeldia gracilis, Eleusine compressa, Dactyloctenium aegyptium, Sporobolus helvolus, S. marginatus* and *Dichanthium annulatum.*

Halophytic scrub communities of the peripheral areas of the rann, on an average, have 164–213 plants per ha with 4.4% basal cover. The above-ground biomass ranges from 6–8 q per ha. This scrub stage remains more or less stable as long as the situation prevails. In some of the ranns sand deposition in the form of sand sheet or hummocks gather species of higher successional status, e.g. *Lycium barbarum, Salvadora oleoides, Acacia jacquemontii, Zizyphus nummularia* and *Tamarix aphylla*. Further the improvement of the substratum ultimately may lead to the climax stage of *Salvadora oleoides-Acacia nilotica*. In Pachpadara, the salt basin with a large amount of sand deposition at the periphery is largely dominated by *Prosopis juliflora*, a fifty-year-old introduction of this exotic into the basin. This species has virtually suppressed the growth of indigenous species. *P. juliflora* has 65% relative dominance and a density of 140–160 plants per ha; producing 35–45 q per ha of the above-ground biomass.

Succession

There are two schools of thought, viz. the dynamic concept of Anglo-American School and the statis concept of the European School of Phytosociologists, based on the Clementsian concept (1916), according to which a given climatic zone will have only one potential climax (Monoclimax) i.e. the climatic climax. The monoclimate theory cannot fulfil the criteria for the preclimax to change towards progression, unless and until the whole climate itself changes. Therefore there is much inclination towards the "polyclimax" view, according to which the term climax is used in its ordinary sense—it can be applied to every relatively stable-self perpetuating community that terminates succession (Oosting, 1956).

The vegetation account discussed in this paper indicates that it is adopted to the whole pattern of environmental factors, but demonstrates a clear change along a continuous environmental gradient. Since whatever factors are responsible for plant communities, there is no absolute climatic climax for the whole of western Rajasthan, but, on the other hand, it has shown a polyclimax pattern. Bharucha (1951) and Satyanarayan (1963) favour the polyclimax concept in this tract, whereas Whitekar (1953) prefers the term "prevailing climax" to the plant population occupying the majority of the sites in an area. Shreve (1951) demonstrated that each habitat in each such division of the desert area had its own climax. Therefore it is not possible to use the term climax for desert vegetation.

Champion (1936), Champion and Seth (1964) from the Indian desert, Chaudhari (1960) and Iftikhar Ahmad (1964) from Pakistan recognize *Prosopis-Salvadora* as the climatic climax of the region (monoclimax), indicating that this formation covers an extensive area from the Aravalli range to the Thar Desert into Pakistan. Gupta and Saxena (1972) described seven grassland types in western Rajasthan and they have been incorporated into this paper.

In the dynamic concept of succession all communities, except the climax, are considered the seral stage. Each seral

Anogeissus pendula-Acacia senegal
(Climax)
⇅
Maytenus emarginatus
Grewia tenax
Zizyphus nummularia
⇅
Euphorbia granulata
Commiphora weightii
⇅
Barleria prionitis
Dipteracanthus patulus
Indigofera tinctoria
⇅
Lepidagathis trinervis
Blepharis sindica
Tephrosia purpurea
⇅
Aristida, Oropetium
⇅
Bare rock

1.1 (WOODLAND)

Sehima nervosum
⇅
Eremopogon foveolatus
Cymbopogon jwarancusa
Heteropogon contortus
⇅
Eleusine compressa
Cenchrus biflorus
Indigofera cordifolia
Aristida funiculata
⇅
Enneapogon brachystachys
Melanocenchris jacquemontii
Tragus biflorus
⇅
Oropetium thomaeum
⇅
Bare rock

1.2 (GRASSLAND)

Fig. 1. Succession on rocks

stage makes the habitat favourable to its next higher stage and it itself gets eliminated. In arid zones, the successional process is very slow, as the formation of mature soils take pretty long to build up and they are destroyed very easily. In spite of all the limiting factors, the successional process does take place and it may be faster in the initial stage, but may become very slow after the first few phases owing to unfavourable edaphic conditions.

A large-scale destruction of the original vegetation from this part of the country due to heavy pressure of man, and the animal population makes it difficult to reconstruct the whole progressional stage into its correct perspective. Extensive ecological studies in western Rajasthan for the last sixteen years have led to build up the probable successional stages on various habitat which are described as follows:

Hills. The denuded rocks, in initial stages are colonized by tough grasses and forbs species, e.g. *O. thomaeum*, *Tragus biflorus*, *Enneapogon brachystachys*, *Melanocenchris jacquemontii*, *Lepidagathis trinervis* and *Blepharis sindica* (Fig. 1). With the accumulation and build-up of the substratum shrub species, such as *Euphorbia caducifolia*, *Grewia tenax*, *Zizyphus nummularia*, get foothold. Simultaneously, higher grass species, such as *Eleusine compressa* start dominating. The shrub species pave the way for tree species, e.g. *Maytenus emarginatus*, *Moringa cancanesis* and *Cordia gharaf*. If these species remain undisturbed, they appear to end up ultimately in the climax community of *Anogeissus pendula-Acacia senegal*. The soils build-up also helps the grassland community to reach its climax with *Sehima nervosum* (Fig. 1.2). The slow build-up of the soil arrests the grassland community to the *Eleusine* stage only. In the higher-rainfall zone, grass species, e.g. *Hackelochloa*, *Bothriochloa* and *Brachiaria*, maintain tke disclimax for *S. nervosum* types of grasslands. Studies carried out in a twenty years exclosure at the rocky side of Kailana (Jodhpur) have indicated that *Acacia senegal* regenerated at a faster rate and increased to an extent of 169% over the unprotected site. Beside this shrub, species, e.g. *Grewia tenax* and *Zizyphus nummularia*, have also shown some percentage increase over the control. *Commiphora wightii* and *Euphorbia caducifolia* started declining in the first decade (Bhimaya *et al.*, 1964).

Older alluvial plains. Flat alluvial plains and interdunal plains with 0–1% slopes with loamy sand to sandy-loam soils get the invasion of *Aristida*, *Melanocenchris*, *Tephrosia*, *Indigofera* and *Crotalaria* in the early stage of colonization. Under protection, perennial grasses and undershrubs gain the upper hand in three to four years. If the area continues to be undisturbed, spiny species, e.g. *Zizyphus* and *Capparis* gather ascendency, which simultaneously culminates into the climax stage of *Prosopis cineraria* (Fig. 2). The flat older alluvial plains, with heavy soils (clay loam and clay), show deviation in seral stages. Early colonisers are altogether different, i.e. *Dactyloctenium aegyptium*, *Echinochloa* and *Cyperus rotundus* (Fig. 2.1.). These plants provide a base for biennial and perennial species, e.g. *Tephrosia* and *Cynodon*, to establish themselves and dominate. This stage is followed by hardy perennial shrub species, e.g. *Indigofera oblongifolia* and *Cassia auriculata*. These in turn are replaced by *Zizyphus nummularia* and *C. decidua*, and they culminate into the *Salvadora* climax. The sandy-clay-loam soils of older alluvial plains scattered in the higher-rainfall zone (300–500 mm) have an early successional pattern of loamy sand or sandy-loam soils and later the species of both the successional ladder form the intermediate stage which ultimately reach as the disclimax stage of *Capparis-Zizyphus* (common to both types). This stage, under a long period of protection, gains dominance over the climax community of *S. oleoides-P. cineraria*.

The high palatability of *Cenchrus* species results in its quicker eliminations owing to severe grazing. Second, this species cannot stand competition with other weeds under the grazed condition. Thus grazing provides an opportunity for the establishment

2.1 (Clay loam to clay soils)	2.2 (Sandy clay loam soils)	2.3 (Sandy loam to loamy sand soils)
Salvadora oleoides	*Salvadora oleoides* *Prosopis cineraria*	*Prosopis cineraria*
⇅	⇅	⇅
Capparis decidua *Zizyphus nummularia*	do	*Zizyphus nummularia* *Capparis decidua*
⇅	⇅	⇅
Cassia auriculata *Indigofera oblongifolia*	do	*Balanites aegyptiaca* *Calotropis procera* *Eleusine compressa*
⇅	⇅	⇅
Tephrosia purpurea *Cynodon dactylon*	do	*Indigofera* sp. *Crotalaria burhia* *Tephrosia purpurea*
⇅	⇅	⇅
Dactyloctenium aegyptium *Echinochloa colonum* *Cyperus rotundus*	do	*Aristida funiculata* *Eragrostis* sp. *Melanocenchris* sp.
⇅	⇅	⇅
Bare soils	Bare soils	Bare soils

Fig. 2. Woodland succession on older alluvial plains

of less palatable species. *Aristida funiculata*, *C. biflorus*, *Eragrostis* species represent the extent of degradation and *Eleusine compressa* as an intermediate stage (Fig. 3). It may be regarded as a precursor of the penultimate stage of *Cenchrus*.

Dichanthium annulatum grasslands occur in small patches on clay loam to clay soils. This grass is more prevalent in a zone with rainfall above 300 mm. The optimum expression obtained on protected lower piedmont plains had 24 per cent basal cover, with 36 q per hectare of the above-ground biomass. Under grazing stress, it is immediately replaced by less palatable species, such as *Digitaria adscendens*, *Cynodon dactylon*, *Eremopogon foveolatus*, *Eragrostis* and *Cenchrus biflorus* which represent various stages of degradation (Fig. 3.2.) *Cynodon* and *Eleusine* form the intermediate stage in succession. Both these species very much resist overgrazing, but once they are removed or killed, the deterioration of the grassland takes place at a faster rate. *Heteropogon* and *Cenchrus* represent a higher stage of succession with moderate intensity of grazing. Once this stage is given complete protection for more than five years, it records the dominance of *Dichanthium annulatum*.

Sandy undulating plains. The initial colonizers of sandy plains and undulating plains include the annual species. e.g. *Aristida funiculata*, *Gisekia pharnacoides*, *Indigofera linifolia*, *Latipes senegalensis*, *Eragrostis* sp., *Cenchrus biflorus* (Fig. 4). The species make a base for perennial grasses and weeds to establish. These undershrubs and grasses, in turn, are replaced by shrub species such as *Calli-*

Cenchrus ciliaris
C. setigerus

⇅

Eleusine compressa
Cynodon dactylon

⇅

Dactyloctenium sindicum
Digitaria adscendens
Urochloa panicoides

⇅

Indigofera cordifolia
Cenchrus biflorus
Tragus biflorus

⇅

Eragrostis sp.
Aristida adscensionis
A. funiculata

⇅

Bare soils

3.1 LOAMY SAND TO SANDY LOAM SOILS

Dichanthium annulatum

⇅

Cenchrus ciliaris
Heteropogon contortus
Eremopogon foveolatus

⇅

Eleusine compressa
Cynodon dactylon
Indigofera sp.

⇅

Brachiaria sp.
Urochloa panicoides
Cenchrus biflorus

⇅

Eragrostis sp.
Tragus biflorus
Cyperus sp.

⇅

Bare soils

3.2 MEDIUM HEAVY TO HEAVY SOILS

Fig. 3. Grassland succession on older alluvial plains

gonum, *Leptadenia* and *A. jacquemontii*, forming the intermediate stage which has a larger coverage. When this stage remains undisturbed for long period it runs into the penultimate stage of *Prosopis cineraria*. Loose sandy calcareous soils of the 100–250 mm zone of rainfall are initially colonized by annual species of *Cenchrus* and *Eragrostis*. These are replaced by *Eleusine* and *Dactyloctenium* which, under a few years of protection, lead to the preponderance and dominance by *Lasiurus sindicus*, the climatic climax grassland of this zone.

Younger alluvial plains. This habitat, being highly potential is never allowed to gain climatic climax. More often, the successionary processes are held up at the pre-climax stage. The rate of succession is farily rapid because of the availability of more moisture throughout the year. Almost all the trees, which grow in this habitat are more or less phaeratophytics. Fallow or abandoned fields in two to three years are colonized by *Cyperus* sp., *Solanum surattense*, *Xanthium strumarium*, *Tephrosia purpurea* and *Crotalaria burhia*. These species provide a base for perennial shrub species, e.g. *Tamarix eriocoides*, *Vitex negundo* and *Leptadenia pyrotechnica*. These species are subsequently replaced by spiny shrubs, such as *Balanites aegyptiaca*, *Zizyphus nummularia* and *Capparis decidua*. This disclimax stage, if left undisturbed, culminates into a climax community of *Acacia nilotica-Prosopis cineraria* (Fig. 5).

Along the dry river courses, some parts of the plains are liable to inundation and they show the dominance of *Desmostachya bipinnata* community. This community, on an average produces 24.5 q per ha of the above-ground forage biomass, with 7% basal cover. Excessive grazing and cultivation lead to degradation with 2–5% cover and 7.5 q per ha of the above-ground biomass. This grass is only slightly palatable in its early vegetative growth period as compared with other perennial and annual forage species. Clumps of *C. ciliaris* and *C. setigerus* are invariably encountered. Their occurrence indicates that these two species may be the potential disclimax of this habitat. Continual cultivation and grazing do not permit these palatable grasses to dominate. *Desmostachya*, being only

4.1 Grassland

Lasiurus sindicus

⇅

Cymbopogon jwarancusa
Cenchrus sp.

⇅

Eleusine compressa
Dactyloctenium sindicum

⇅

Cenchrus biflorus
Latipes senegalensis

⇅

Indigofera linifolia
Eragrostis spp.
Aristida adscensionis

⇅

Aristida spp.
Mollugo sp.

⇅

Loose sand

4.1 Grassland

4.2 Woodland

Prosopis cineraria

⇅

Tecomella undulata
Maytenus emarginatus

⇅

Zizyphus nummularia
Acacia jacquemontii
Balanites aegyptiaca

⇅

Calligonum polygonoides
Lycium barbarum
Mimosa hamata

⇅

Panicum turgidum
Lasiurus sindicus
Crotalaria burhia

⇅

Cymbopogon jwarancusa
Eleusine compressa
Dactyloctenium sindicum

⇅

Indigofera linifolia
Latipes senegalensis
Cenchrus biflorus

⇅

Aristida sp.
Gisekia pharnacoides
Mollugo nudicaulis

⇅

Loose sand

4.2 Woodland

Fig. 4. Succession on sandy undulating hummocky plains

slightly palatable, regenerates with its strong rhizomes and resists rigorous cultivation practices. *Cyperus rotundus*, *Cenchrus biflorus*, *Aristida* and *Eragrostis* species are the initial colonizers (Fig. 5), and these species persist year after year of cultivation. On the other hand, fields under long fallows show the dominance of *Eleusine compressa*, with a few clumps of *Cenchrus* sp. and *Desmostachya*. The return of *Desmostachya* turns the whole field into its grassland. Once established, it is very difficult to eradicate this grass. Pretty long undisturbed condition may lead to dominance by *Saccharum*.

Sand-dunes : Various stages of development or degradation of plant communities on the sand-dunes are encountered in western Rajasthan. Out of those stages, one can reconstruct its successional pattern. *Cyperus arenarius*, *Aristida funiculata*, *Cenchrus biflorus*, *Indigofera cordifolia*, *I. argentea*, *Farsetia hamiltonii*, *Crotalaria burhia* and *Aerva pseudotomentosa* are the pioneer species (Fig. 6). A large-scale coverage by *Crotalaria*, *Aerva* and *Cyperus* sp. brings about the stabilization of sand to a greater extent. Now, the substratum be-

Saccharum sp.

⇅

Desmostachya bipinnata

⇅

Cenchrus species

⇅

Eleusine compressa
Dactyloctenium sindicum

⇅

Indigofera cordifolia
Cenchrus biflorus
Eragrostis spp.

⇅

Aristida sp.
Cyperus rotundus

Bare soil

5.1 GRASSLAND

Acacia nilotica
Prosopis cineraria

⇅

Capparis decidua
Zizyphus nummularia

⇅

Balanites aegyptiaca
Leptadenia pyrotechnica

⇅

Tamarix eriocoides
T. troupii
Vitex negundo

⇅

Desmostachya bipinnata
Xanthium strumarium

⇅

Crotalaria burhia
Tephrosia purpurea

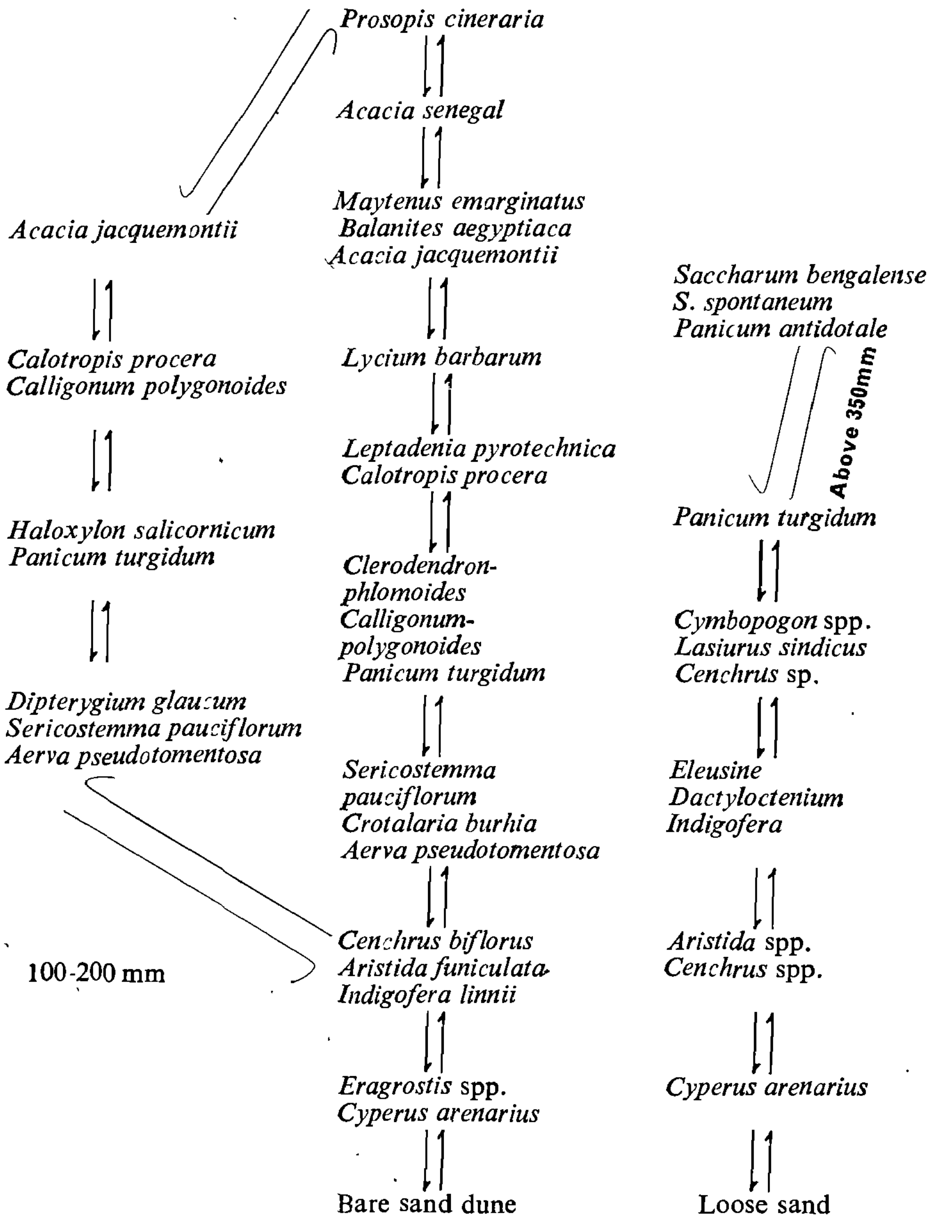
⇅

Solanum surratense
Cyperus sp.

Bare soil

5.2 WOODLAND

Fig. 5. Succession on younger alluvial plains.



6.1 WOODLAND (200–350 MM) 6.2 GRASSLAND (200–350 MM)

Fig. 6. Succession on sand dunes

Dichanthium annulatum
Sporobolus marginatus

⇅

Sporobolus sp.

⇅

Eremopogon foveolatus
Cenchrus species

⇅

Eleusine compressa
Echinochloa colonum
Dactyloctenium aegyptium
Chloris virgata

⇅

Aeluropus lagopoides

⇅

Cyperus rotundus
Scirpus sp.

⇅

Clayey saline soils

7.1 GRASSLAND

Salvadora oleoides-
Acacia nilotica

⇅

Tamarix aphylla
Zizyphus nummularia
Capparis decidua

⇅

Haloxylon salicornicum
Suaeda fruticosa
Salsola baryosma

⇅

Sporobolus marginatus
Desmostachya bipinnata
Peganum harmala

⇅

Eleusine compressa
Schoenfeldia gracilis
Chloris virgata

⇅

Trianthema portulacastrum
Portulaca oleracea
Cressa cretica

⇅

Aleuropus lagopoides
Cyperus rotundus
Scirpus sp.

⇅

Clayey saline soils

7.2 WOODLAND

Fig. 7. Succession on saline depressional areas 'Rann'

comes more suitable for invasion by undershrub, shrubs and perennial grasses, e.g. *Sericostemma pauciflorum*, *Leptadenia pyrotechnica*, *Clerodendron phlomoides*, *Calligonum polygonoides*, *Calotropis procera*, *Panicum turgidum*, *P. antidotale*, *Lasiurus sindicus* and *Cenchrus ciliaris*. Subsequent stabilization and undisturbed conditions bring about *Acacia jacquemontii*, *Lycium barbarum*, *Balanites aegyptiaca* and *Maytenus emarginatus*. The last three species form the penultimate stage for the climax community of *Prosopis cineraria*. The grassland development in the low-rainfall zone (below 300 mm) gets arrested up to *Panicum turgidum* type only, whereas in the higher-rainfall zone (above 350), the same stage is surpassed by *Saccharum* species.

The highest grass community is represented by *Saccharum bengalense*.

Saline depression. Sporobolus marginatus represents the optimum expression of the grasslands of the saline habitat. When nngrazed, a pattern of grass communities develops, according to the micro-relief and silt concentration in the soils. *Dichanthium annulatum* establishes itself near trenches and bunds where most of the salts are leached out during the rains. The most salt-tolerant grass is *Aeluropus lagopoides* which comes right on the salt incrustation. Water-logged areas support *Cyperus* and *Scirpus* species. The earlier colonizers are (Fig. 7) *Zygophyllum simplex*, *Cressa cretica*, *Sensuvium portulacastrum*, *Schoenfeldia gracilis* and *Chloris virgata*. Here again, *Eleusine compressa* forms the intermediate stage in the successional ladder. The leaching of salt and subsequent sand deposition on such a habitat stages the arrival of shrub species, such as, *Suaeda fruticosa*, *Salsola baryosma*, *Haloxylon salicornicum*, *Zizyphus nummularia* and *Tamarix* species, which continue to grow as disclimax. A further improvement of these species may lead to the penultimate stage of *Salvadora oleoides-Acacia nilotica*.

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20

MEASURING DESERTIFICATION THROUGH PLANT-INDICATORS

VINOD SHANKAR

THE relationship of the species amplitudes and quantities to the environmental gradients has found many practical applications. The development of plants, *inter alia*, to read out the environmental gra-, dient is one of them. The environmental gradient sought to be explored may be single or a combination of both, and may be temporal and spatial. For a purpose like the measurement of desertification with the aid of plant-indicators, stress is laid on selecting criteria out of the temporal developments within a specified habitat. While going in for the selection of plant-indicators and working out a score-card for measuring desertification trends in western Rajasthan, the approach has been similar to that adopted for the range-condition surveys (Dyksterhuis, 1958).

To build up the guidelines for the selection of criteria and for the grading of the scores, an attempt was first made to scan through the pertinent literature to search out the very premise on which the whole thing would be developed. The enquiry about the premise was as to what the desert formation would be a woodland, a shrubland, a grassland or a savanna type. Whether a reconstruction of the past vegetation and a link-up with the present one is possible or not. The enquiry, to put into simple words, was as to how the past vegetation looked like and what relationship, if any, the present vegetation would have with it.

Palaeobotanical evidences gathered so far reveal that (1) western Rajasthan supported a tropical rain-forest during the Tertiary, (2) the present-day xerophytic vegetation was well established at the beginning of the Holocene (10,000 years B.P.) and (3) no palaeobotanical records belonging to the 50 million years that elapsed between the two epochs are available. The Holocene vegetation was, therefore, chosen as a starting-point. Attempts were made (Singh, 1967, 1969; Singh *et al.*, 1972, 1974; Meher-Homji, 1970, 1973; Vishnu-Mittre, 1975) to reconstruct the physiognomy of the Holocene vegetation. The soundness of this however, seems to have suffered because of (1) the lack of real knowledge of the micro- and macro-transitional phases in vegetation-environment interactions, and (2) deflected succession caused by biotic influences. The gross reconstruction (Singh *et al.*, 1974), the climo-vegetation relationship (Legris and Meher-Homji, 1975) and the successional trend in the past vegetation (Vishnu-Mittre, 1975) is, nevertheless, a worthy attempt. For the purpose, enunciated in this paper, it has been broadly accepted that a shrub-savanna, with species content varying according to the habitat, was a bio-edaphic disclimax during the Holocene. Vishnu-Mittre (1975) calls it climax vegetation but it does not appear to be a very wise and viable proposition.

It becomes clear from the foregoing account that for measuring desertification in terms of vegetation parameters, the following points must be kept in view: (1) A shrub-savanna was the desert formation, (2) the relationships between the landform and the plant cover were similar to what are now, (3) abusive land use in the form of overgrazing, excessive felling, shifting cultivation, burning, etc. brought about deterioration in the shrub-savanna formation, (4) the knowledge of the ecological status of plants and their habitat, as obtaining now (Satyanarayan, 1964) can be employed to numerically express the degree of desertification. In doing so, there is no denying the fact that an element of subjectivity and a justifiable limit of arbitrariness in assigning numbers to each parameter remain and all this can be further improved upon.

THE SCORE CARD

The parameters selected are the ecological status and the developmental stage of the vegetation, analytical attributes of perennial grasses, including dominance on production basis, vigour of perennial grasses, weeds, shrubs and the grazing or browsing intensity.

Plant-indicators	*Check points*
1. *Ecological status and developmental stage*	
1·1 Stage final (disclimax)	1
1·2 " fourth (2nd or penultimate sere)	3
1·3 " second (2nd seral stage)	5
1 4 " first (pioneer colonizers)	7
2. *Relative importance value index (summation of relative frequency, relative density and relative basal cover) of perennial grasses*	
2·1 76 to 100	1
2·2 51 to 75	3
2 3 26 to 50	5
2·4 0 to 25	7
3. *Dominance (on the basis of dry-matter yield)*	
3·1 Exclusive dominance of higher perennial grasses	1
3 2 A mixed stand of higher and lower perennials	3
3·3 Exclusive dominance of lower perennials	5
3·4 Patchy distribution of annual grasses	7
4. *Vigour of perennial grasses*	
4·1 Normal vigour under protection (robust, dark green plant not pedestalled)	1
4 2 As above, plant slightly pedestalled	3
4·3 Vigour medium, plant obviously pedestalled or pillow form	5
4 4 Vigour poor, roots exposed, distinctly pedestalled or pillow form	7
5. *Weeds*	
5 1 Rare	1
5·2 Occasional	2
5·3 Frequent	3
5·4 Abundant	4
6. *Shrubs*	
6 1 Crown cover 14% or less	1
6·2 " " 15 to 25%	3
6 3 " " 26 to 39%	5
6·4 " " 40% and over	7
7. *Grazing intensity*	
7 1 Zero grazing (0)	1
7 2 Light grazing (less than 25% herbage removed)	3
7·3 Moderate grazing (26–50% herbage removed)	5
7 4 Heavy grazing (51% and above herbage removed)	7

Magnitude of desertification:

Grading		*Score*
1. Zero	=	7 and below
2. Light	=	8 to 20
3. Moderate	=	21 to 33
4. Heavy	=	34 to 46
5. Severe	=	47 and above.

CONCLUSION

The objective of the above score-card is to measure negative and positive changes in the ecological status of the plants caused by biotic factors, specially the herbivory. Such changes can be seen from comparisons between the disturbed vegetation and the relict or reserve vegetation. The applied use of the score-card includes its use from the angle of range management, as it considers the plant-indicators within the broader framework of an open xeromorphic scrub vegetation. From the forestry angle, the ecological status of the plants has to be fixed with the open xeromorphic woodland as a marker and the tree parameters and not with the under storey.

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21

FOREST-TREE PLANTING IN ARID ZONES

R. N. KAUL AND GYAN CHAND

THE establishment of social and protective forests in low-rainfall zones is an effective means of raising the level of the local economy and improving the ecology of these regions. Rehabilitation by tree-planting is by no means restricted to areas that formerly bore forest growth. Even in the regions that apparently had always been devoid of trees, transplanting is not only feasible but extremely important in any programme of land improvement. It is estimated that between 300 and 500 million seedlings of forest trees are planted every year in the arid and semi-arid zones of the world with varying degrees of success. This paper describes the techniques and species of proven merit for large-scale tree-planting in the Indian arid zone under varying edaphic and climatic conditions.

SILVICULTURAL PROBLEMS

The most urgent practical problem in applied silviculture is the development of practical methods for afforesting different land types met within the arid zone, with utilizable species. This problem demands studies on : (i) the selection of species, both indigenous and exotic, and their ecotypes for different sites; (ii) the production of seedling transplants; (iii) silvicultural characteristics of selected tree and shrub species; (iv) soil-working techniques and cultural operations in relation to the harnessing of the uncertain and erratic rainfall, particularly during periods when the lack of soil moisture is felt most; and (v) protection against diseases and vertebrate pests. With these problems in view, a research programme was formulated and initiated in 1958 at the Central Arid Zone Research Institute, Jodhpur, and the results obtained are briefly discussed below:

FOREST SPECIES AND VARIETIES

Introduced species. The local tree species of the region are not only a few but are also extremely slow-growing and it, therefore, becomes necessary to introduce tree species of higher growth rate and of better resistance to drought and cold. One hundred and twelve species of different provenances of *Eucalyptus*, 64 species of different provenances of *Acacia*, and 82 species of 44 other genera from more or less isoclimatic regions of the world were tried in the arboreata at Jodhpur and Pali.

Eucalyptus. The order of performance of the different species has been different with respect of three growth attributes, namely the percentage survival, height growth, and the diameter at breast height. At Jodhpur, *Eucalyptus melanophloia* has distinctly shown promise, whereas at Pali, *E. tessellasis*, *E. melanophloia*, *E. oleosa* and *E. camaldulensis* have performed well.

Acacia. The *Acacia* species which have shown performance in growth and survival equal to or better than, the indigenous *Acacia senegal* have been designated as promising. Among *Acacia* species *A. tortilis* has proved to be the most promising introduction from Israel. Eight-year-old trees at Jodhpur showed 100 per cent survival. The mean height growth attained was 6.4 m. *A. tortilis* has now been successfully introduced on an extensive scale into the arid and semi-arid regions of the country.

Miscellaneous genera. The species belonging to different genera were selected with a view to meeting the twin objective of providing fodder and shade for animals in rangelands. *Casuarina cristata, Grevillea pterosperma, Myporum montanum, Zizyphus spinachristi, Colophospermum mopane, Schinus molle,* etc. have shown promise (Kaul, 1970).

INDIGENOUS SPECIES

When soil conditions are taken into account, the indigenous species are the best adapted to the local conditions. The only problem in the case of indigenous species is their excessively slow growth rate, at least during the early years. For example, in 14 years *Prosopis cineraria, Acacia senegal* and *Tecomella undulata* under Jodhpur conditions attained a height of 2.8, 3.5 and 3.1 m respectively. The valuable indigenous tree species are *P. cineraria, A. senegal, T. undulata, Albizzia lebbek, Salvadora oleoides* and *Azadirachta indica.*

NURSERY TECHNIQUES

In the nursery, the maximum seedling mortality occurred during August to November and, to a much less extent during February to March; thereafter, no seedling mortality took place till July. Of the four species studied, *Acacia senegal* showed the maximum seedling mortality (8.5 per cent), followed by *Albizzia lebbek* (3.7 per cent), *Tecomella undulata* (3.5 per cent) and *Prosopis cineraria* (2.7 per cent). Changes in the ambient temperature during the juvenile seedling stage (3 months old) of these species appeared to be the cause of seedling mortality.

The seedlings of *Albizzia lebbek* and *Prosopis juliflora* in metallic containers showed higher survival rates and growth in height than those in earthen pots. Metallic containers also resulted in economy in watering to the extent of 25 per cent as compared with earthen containers. In general, the increased levels of watering resulted in increased survival and growth in height of *A. lebbek* and *P. juliflora.* However, nine litres of water at a time per set of 50 containers was found to be the most economic dose of watering for the successful raising of nursery seedlings. When grown in shade, the water need of seedlings was less by 9.6 per cent than the need of those grown in the open. Seedlings kept in cemented beds under nine litres of watering level required 29.8 per cent less water than those kept in earthen beds because of a smaller number of root clippings in cemented beds. The use of metallic containers effected an overall economy of Rs 6 in the production per 100 seedlings (Kaul and Ganguli, 1963b).

Further studies on the media and sizes of receptacles for growing nursery stock of four desert tree species, namely *Albizzia lebbek, Acacia senegal, Prosopis cineraria* and *Tecomella undulata,* showed superiority of the metallic containers to those made of baked earth and polythene. Larger containers compared with smaller ones proved better for seedling survival and growth (Kaul and Gyan Chand, 1967).

Nursery trials were carried out to test the growth-promoting effect of gibberellic acid (G.A.) on three indigenous species, viz. *Prosopis cineraria, Acacia senegal* and *Albizzia lebbek,* and two exotic species, viz. *Eucalyptus camaldulensis* and *Acacia tortilis,* with a view to shortening the period required for seedling growth in the nursery. In general, the indigenous species did not show a significant increase in the shoot growth of the treated seedlings over that of the control seedlings. The seedlings of *Acacia tortilis* showed the maximum increase in shoot growth under 10 ppm of G.A. treatment, though this difference was not significant when compared with the control treatment. Treated seedlings of *E. camaldulensis* showed a significant increase in height growth of shoots as compared with that of the control ones, the maximum increase being under 30 ppm G.A. treatment. Similar trends were observed in respect of shoot-to-root ratio. The lack of response of the three indigenous species to the application of G.A. is probably due to the natural presence of optimal amounts of this chemical in them (Kaul, 1964b).

Different sizes of root and shoot cuttings of *Prosopis juliflora*, varying in collar diameter and root length, influenced the sprouting period, whereas the survival in the nursery was affected by root length alone. Root-shoot cuttings of 1.5-cm collar diameter and 17.5-cm root length in the case of *Prosopis juliflora* appeared to be the most suitable sizes for pre-sprouting them in the nursery (Bhimaya *et al.*, 1965).

SILVICULTURAL CHARACTERISTICS OF INDIGENOUS TREE AND SHRUB SPECIES

Age of seedlings. The data recorded at the end of 10 years revealed that one-year-old seedlings of *Prosopis cineraria* (99.1 per cent), two-year-old seedlings of *Albizzia lebbek* (67.5 per cent), and one-year-old seedlings of *Acacia senegal* (95.8 per cent) exhibited the highest survival although, differences within a species among the ages of seedlings (6-,9-,12-, and 24-month-old seedlings) were not significant.

Time of planting. Prosopis cineraria (97.5), *Albizzia lebbek* (60), *Tecomella undulata* (90.8) showed the maximum percentage of survival when planted in the second fortnight of July as compared with plantings in first fortnight of July and the first fortnight of August. There was, however, no significant differences among the three planting periods. The best planting period synchronizes with the onset of the monsoon (Kaul, 1964a).

Soil-working and the method of reboisement. Compared with direct seeding, transplanting proved to be an assured method of reboisement in the case of *Prosopis cineraria, Acacia senegal, Albizzia lebbek* and *Tecomella undulata.* Soil-working comprising 60 cm^3 half-filled pits with a crescent-shaped ridge across the local slope resulted in a higher rate of establishment.

Root characteristics. The initial root habit of a given species, its ramifications and its inherent capacity for adjustment to variations in soil moisture conditions appear to be very important factors in seedling survival in the first growing season following germination as evidenced in the case of *Albizzia lebbek* and *Tecomella undulata.* However, a very low inherent top-root ratio appears to bring about a better hydro-economic effect resulting in greater initial seedling survival as in the case of *Acacia senegal.* The root-system characteristics of *Prosopis cineraria* seedling, however, do not have the drought-escaping properties at least in the juvenile seedling stage (Bhimaya and Kaul, 1966). Further studies on six-year-old plants of *T. undulata, A. lebbek, P. cineraria* and *A. senegal*, obtained from direct seeding and transplanting, revealed that the transplanted plants of all the species showed an increased length of the tap-root. The species did not differ markedly in their maximum lateral spread of root under seeding and transplanting. The transplanted plants of all the species, excepting *T. undulata* recorded an increased number of secondary roots compared with plants raised from direct seeding. The transplanted plants of *T. undulata* and *A. senegal* showed a higher root-shoot ratio, whereas the plants of *A. lebbek* and *P. cineraria* raised from direct seeding showed a higher root-shoot ratio (Bhimaya and Kaul, 1965).

Spacing. When planted at a spacement of 1.6 m × 1.6 m, the crowns of these species touched each other within seven years, thus necessitating thinning. Since in the arid environment these species do not attain any usable size within this period, it is better to follow an initial wider spacing (at least 3.5 m), as that will not only obviate the necessity of early intermediate thinning but will also be conducive to a better plant growth and facilitate mechanical weeding in the plantation.

PLANTING TECHNIQUES IN RELATION TO LAND TYPES

The special features of soil-working

techniques and cultural methods for the establishment of plantations in different land types are briefly summarized below:

Shifting sand-dunes. In low-rainfall areas (150 mm to 400 mm), shifting dunes are commonly met with, particularly near habitations and townships. Techniques of afforestating the shifting dunes were standardized after 10 years of experimentation (Kaul, 1970). These techniques consist of (i) protection against biotic interferences; (ii) the treatment of shifting sand-dunes by fixing barriers in parallel strips or in a chess-board design, using the local shrub material starting from the crest down to the heel of the dune to protect the seedlings from burial or exposure by the blowing of sand; and (iii) afforestation of such treated dunes by direct seeding and planting. The two species commonly used for erecting brushwood barriers (Micro-windbreaks) are *Zizyphus nummularia* and *Crotalaria burhia.* The direct seeding of grass species and creepers is carried out in lines, 2 to 5 metres apart, on the leeward side of the micro-wind break. The nursery stocks are raised, either in containers or in specially prepared sun-dried planting bricks, consisting of a mixture of sand, clay and farmyard manure in the ratio of 1:1:1, with a height of 30 cm and a cross-section at the top and bottom of 10 cm and 15 cm square respectively. When transplanted at this stage, a high degree of establishment is achieved.

The indigenous and exotic species which have proved successful are: Trees—*Acacia senegal*, *Prosopis juliflora* (in non-frosty localities only), *Albizzia lebbek*, *Cordia rothii*, *Dalbergia sissoo* (in regions with mean annual rainfall of 250 mm) and *Zizyphus jujuba*; shrubs—*Calligonum polygonoides*, *Cassia auriculata*, *Ricinus communis* (in non-frosty localities), and *Zizyphus nummularia*; grasses—*Lasiurus sindicus*, *Panicum turgidum* and *Erianthus munia* (Bhimaya *et al.*, 1964). Among exotic species, *Eucalyptus oleosa* (Australia), *Acacia tortilis*, *Parkinsonia aculeata* and *Acacia victoriae* (Australia) were found to be promising, especially, as these species were found to be frost-resistant.

Sand-dunes afforested in this way showed wide variations in fuel yield, both in respect of the age of the tree and the habitat. The difference in fuel yield between the habitats followed the pattern of increase in the rainfall from west to east (Bhimaya *et al.*, 1967).

The data on the expenses incurred and the revenue from fuel, fodder, seeds and other things for the sand-dune stabilization areas of the Bikaner and Jhunjhunu districts indicate that the technology of sand-dune stabilization had a break-point even after 15 years. The average cost per hectare, including fencing, mulching, afforestation, major repairs and operational costs worked out at Rs 551.60 for Udramsar, Rs 753.76 for Shri Kolayatji, Rs 1,039 for Shivbari and Rs 455.50 for the Jhunjhunu areas. The average benefits per hectare comprising fuel, fodder, *munja*, forage grasses, tree seeds, etc. came to Rs 1,560 for Udramsar, Rs 616 for Shri Kolayatji, Rs 637 for Shivbari and Rs 2,086 for the Jhunjhunu areas (Gyan Chand *et al.*, 1976).

Shallow soils. Earlier experiments on the establishment of three seedlings on shallow soils (22.5 cm deep) overlying hard calcareous pans under a rainfall of 375 mm showed that *Albizzia lebbek*, *Eucalyptus camaldulensis* and *Casuarina equisetifolia* gave the highest seedling survival in pits 30 cm in diameter and 60 cm deep (Bhimaya and Kaul, 1969). *Casuarina equisetifolia* subsequently failed to establish itself, whereas the other two species remained stunted and did not put on any appreciable increment even after seven years of growth. Subsequent experiments with deep soil-working in pits, 60 cm in diameter and 90 cm in depth perforating much of the hard-pan consistently resulted in cent per cent survival and a mean annual height increment of 28.9 cm and 25.18 cm in *Azadirachta indica* and *A. lebbek* respectively. Studies have conclusively shown that two weedings, one at the end of July and the other at the end of January are extremely necessary for proper plant growth. The plants of *Acacia tortilis* attained 54.8 per cent increase in the mean annual height increment under the treatment of two weedings a year carried out for the first three years compared with the control. These trees at end of 11 years have attained an average height of 5.6 m and a diameter of 7 cm at breast height.

Studies on soil-working with the direct seeding of *Acacia nilotica* ssp. *indica* and *Prosopis cineraria* have shown that soil-working can be carried out at any time from March to June; that in relatively flat areas a smaller cross-section (30× 30 cm) of ridge-cum-trench is as effective as that of a wider cross-section (60× 30 cm) and that a progressive spacing of seedlings, by removing excess seedlings during the first two years of seeding, is extremely essential for proper seedling growth (Kaul and Gyan Chand, 1966). In shallower soils, transplanting in 0.3-m-deep pits compared with direct seeding has been found to be a better technique for raising plantations.

Semi-rocky areas. Semi-rocky areas are characterized by their shallow depth at the foothills in the 225-to-350-mm rainfall tract and are formed by colluvial silt and rock fragments. Among the different soil-working techniques tried in the experimental afforestation on 283 hectares, the seeding of *Acacia senegal*, *Prosopis juliflora*, *Tecomella undulata*, *Acacia nilotica* ssp. *indica*, and *Prosopis cineraria* on staggered contour ridge-cum-trenches, each 2 m in length and 60 × 60 cm in cross section, proved successful. Among these species, at the end of 9 years, the maximum survival was recorded in the case of *P. juliflora* (50 per cent), followed by *A. senegal* (30 per cent) and *Cassia auriculata* (15 per cent). However, the average increases in height and diameter at breast height recorded for these species were : *P. juliflora*—4.8 m and 3.2 cm; *A. senegal*—1.5 m and 1.4 cm; and *C. auriculata*—1.3 m and 2.5 cm respectively.

Planting was done in 60 cm^3 half-filled pits with a crescent-shaped ridge across the local slope. Pre-sprouted stumps of *Prosopis juliflora* showed 98 per cent survival and a mean growth in height of 4.8 m at the end of 9 years. *Albizzia amara* (96 per cent), *Azadirachta indica* (95 per cent), and *Holoptelia integrifolia* (90 per cent) were next in order of percentage survival. Recent studies indicate that *Acacia tortilis*, having exhibited 100% survival and a height growth of 6 m at the end of 5 years, is the most promising of all the species that have so far been tried.

Rocky areas. Barren rocky hills, covering extensive areas form one of the characteristic features of the landscape. Studies show that only those patches where the depth of soil of about 43.5 cm has accumulated should be planted with tree species. Pre-sprouted stumps of *Prosopis juliflora* in 60 cm^2 half-filled pits and direct seeding of *Acacia senegal* on ridges have given reasonably good establishment.

Recent studies on the comparative performance of *Acacia tortilis* and *Acacia senegal* under direct seeding and transplanting showed that *A. tortilis* attained three times more growth in height under both the methods than *A. senegal* and is likely to do better in such land types. Recent studies (Kaul *et al.*, 1966) revealed that in the piedmont geomorphic units, soils depth was highly related to microrelief and that it should be taken as an important factor in the planning of afforestation in such areas.

Roadside avenue and wind-break planting. Experimental shelterbelts in the form of roadside avenue along the principal highways were established in different parts of the region to the extent of 200 km at a cost of Rs 625 per km.

The technique consisted in planting three staggered rows of trees on each side of the road (Kaul, 1957). In low-rainfall (120 to 350 mm) tracts, the regular watering of plants at 9 litres per seedling during the summer months for at least the first two years after planting, and with tree guards as protection against cattle gave a survival percentage of 62.4. The species in order of performance were *Prosopis* *juliflora*, *Azadirachta indica* and *Albizzia lebbek*. In moderate-rainfall (350 mm) tracts, these species, under similar treatments, gave 95 per cent survival, whereas in the higher-rainfall zone (400 mm), *Azadirachta indica*, *Albizzia lebbek* and *Dalbergia sissoo* achieved 80–90 per cent establishment without supplemental irrigation. Recent trials on the comparative efficiency of different methods of protection, viz. one-metre-wide tree-guard (made out of empty coal-tar drums) and the usual circular ridge-cum-trench have shown that the former method is more efficient in the case of species with wide-spreading lateral roots, such as *Acacia tortilis*, whereas the latter method appeared to be suitable for deep-rooted species. Narrow tree-guards, 45 cm in diameter, were found to be inimical to plant growth.

Successful shelterbelts of *Acacia nilotica* ssp. *indica* and *Dalbergia sissoo* were established over a length of 102 km at the Central Mechanized Farm, Suratgarh, in the Bikaner District. The soil-working consisted in digging ditches of triangular cross-section, i.e. 45 cm wide and 45 cm deep, along the planting line with a mechanical ditcher. Planting-pits, 30 cm^3, were dug staggered with one another on both sides of the ditches. The seeding of *A. nilotica* ssp. *indica* were carried out on each side of the ditch in such a way that the sown lines remained just above the level of irrigation water whereas the pre-sprouted stumps of *D. sissoo* were planted in the pits. The cost of raising such shelterbelts worked out at Rs 330 per km (Bhimaya and Chowdhari, 1961).

SILVI-PASTORAL APPROACH TO LAND USE

Considering that livestock husbandry occupies the most important place in the economy of the arid region and that frequent droughts results in a loss of cattle wealth owing to the shortage of fodder resources, it is necessary that range improvement should be complemented with the raising of fodder tree and shrub species which not only give the much-needed forage during the scarcity periods, but also give shade and shelter to the grazing animals, thereby help to utilize forage uniformly on the range. In addition, fodder trees and shrubs will ameliorate the micro-climatic conditions and thereby create conditions conducive to the natural regeneration of grasses which are higher in succession. Studies have shown that a density of 14 per cent of *Zizyphus nummularia* is optimum for increased forage production (Kaul and Ganguly, 1963a). *Prosopis cineraria* is an important forage-tree species which grows in cultivated fields (sometimes more than 60-80 trees per hectare) without any detriment to the crops grown in association with it. The tree is lopped for its protein-rich (17.49 per cent) leaves. Studies have shown that complete lopping (lopping of the entire tree) gives a significantly higher fodder yield (58-72 kg per tree) than the lopping of the lower two-thirds (28.48 kg per tree); and the lower one-third (19.73 kg per tree) of the crown. There was no significant difference between two-thirds and one-third lopping treatments (Bhimaya *et al.*, 1964). Sixteen indigenous tree and shrub species which have been found to be browsed by different species of livestock at one time or another have been studied for their palatability and nutritive value (Ganguly *et al.*, 1964). Among the many exotic fodder tree species tried at Jodhpur and Pali, *Acacia aneura* (Australia), *Pittosporum phillyraeoides* (Australia), *Brasilettia mollis* (Venezuela), *Geoffroea decorticans* (Chile), *Prosopis alba* (Argentina) and *Colophospermum mopane* (Southern Rhodesia) showed great adaptability. All these species had flowered and produced viable seeds. *C. mopane* was even found to be naturally regenerating in the arboretum at Jodhpur (Kaul, 1970). It is, therefore, necessary that the planting of fodder tree and shrub species should form an essential part of any range-improvement programme in the arid zones.

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22

IMPROVING RANGELAND PRODUCTIVITY

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ARID zones are marked by hostile agro-climatic conditions and frequently recurring famines because of scanty and erratic rainfall. The local people obtain their sustenance from livestock to ameliorate their plight. Livestock is dependent mostly on native rangelands which have become degraded and denuded owing to a high pressure of livestock-grazing. With a view to evolving scientific technology for speedy regeneration, the improvement and utilization of such rangelands, studies were initiated on 52 paddocks, each of about 80 hectares (in 10 districts of western Rajasthan, India), under different habitats and different class rangelands (Table 1) in 1959 to find out suitable-techniques for upgrading the existing rangelands and utilizing them.

The number of paddocks was reduced to 28 and 12 during 1963 and 1969 respectively. The main results obtained are reviewed as under:

Selection of sites. It will be desirable to take up pasture development at the outset in such class of lands, in areas with easy accessibility and water facility, so that local people can visit the places frequently and realize the value of such development. A long-term grass-crop rotation is desirable on class IV lands to reduce erosion hazards, improve soil fertility and vegetative production.

Fencing. In this part of the country, no development project involving land can be successful without proper fencing because of heavy livestock pressure. Among various types of fencing, viz. the one with barbed wire with different posts, e.g. angle-iron, stone and wooden posts; ditch and bund, corewall and thorns, stone wall, live hedge with cactus tried and studied, it has been found that angle-iron posts with a fencing of barbed wire is by far the most effective and economical means in the long run. With proper maintenance, it can last for over 20 years (Bhimaya *et al.*, 1966; Mann and Ahuja, 1975). As iron or steel material is not easily available, trench and corewall fencing, corewall

Table 1. Distribution of different rangeland paddocks under experiment

Condition of rangeland	Average annual rainfall above 380 mm		Average annual rainfall below 380 mm		Total
	Heavy soils	Light soils	Heavy soils	Light soils	
Poor	6	6	5	8	25
Fair	5	4	2	7	18
Good	3	2	2	2	9
Total	14	12	9	17	52

thorn fencing, etc. may be constructed on co-operative or "sharamdan" basis by villagers during the forced idle period or lean periods and such types of fencing need regular care and repairs, otherwise they do not serve any purpose at all. The present cost of angle-iron posts and barbed-wire fencing is Rs 9 per running metre. The smaller the size of the block, the greater is the proportionate cost per hectare (Ahuja, 1975).

Forage production. Grassland cover of this region is *Lasiurus-Cenchrus—Dichanthium*; *Lasiurus sindicus*, *Cenchrus ciliaris*, *Cenchrus setigerus* and *Dichanthium annulatum* are the climax grasses (Dabadghao, 1960). Owing to indiscriminate overgrazing because of high livestock population, rangelands have reached the last stage of degradation. About 80 to 90 per cent of rangelands are under 'poor' to 'very poor' condition class (Raheja, 1962). Those under climax to subclimax cover have existed owing to highly restricted grazing under severe water scarcity (Ahuja and Bhimaya, 1966a).

Efficient grassland management aims at the maximum utilization of forage without undue interference with growth and vigour of important fodder and other useful species. With protection and grazing, the native range on the carrying capacity, aiming at 70 per cent forage-utilisation level, the forage yield increased. The data on forage yield under different condition classes of rangelands for six years are presented in Table 2.

The forage yield on rangelands after two years of protection and controlled grazing increased by 148.3, 91.9 and 116.3 per cent in 'poor', 'fair', and 'good' condition classes respectively. The rangelands of 'good' condition class were obtained in 1960; and the data are presented for that year onwards. Rainfall in 1962, 1963 and 1964 was below normal and of shorter duration; the forage yields did not show any appreciable increase (Bhimaya *et al.*, 1967).

Detailed studies on 12 range-management paddocks for 14 years revealed that forage production varied with rainfall; within different rainfall zones, forage production was higher on heavier soils. Data pertaining to the average forage yield on rangelands under different land forms are presented in Table 3.

Forage yields increased as the rainfall increased from western to the eastern Rajasthan. Forage production was also found to be dependent on habitat, particularly the soils for obvious reasons. Production was low on shallow gravelly habitat and highest on heavy deep soils.

Grubbing of unwanted bushes. Unwanted thorny plants, such as *Lycium barbarum*, *Balanites aegyptiaca*, *Acacia leucophloea* and *Mimosa hamata*, which hinder the growth of grass species and are too troublesome to grazing animals should be

Table 2. Forage yield (air-dried kg/ha) in different types of rangelands in arid zone

Type of rangeland	Year of observations						
	1959	1960	1961	1962	1963	1964	1965
Poor	337 (9)	450 (21)	837 (18)	688 (12)	642 (8)	770 (9)	885 (9)
Fair	552 (10)	873 (22)	1,065 (21)	869 (17)	817 (11)	1,074 (10)	835 (10)
Good		704 (4)	1,068 (6)	1,523 (8)	1,263 (9)	1,480 (8)	1,163 (8)

(Figures in parentheses indicate the number of paddocks studied.
Source: Bhimaya *et al.*, 1967).

Table 3. The forage yield (air-dried, in kg/ha/year) on rangelands under different rainfall and soil conditions (average of 14 years 1959–72)

S.No.	Rainfall zone and the names of substations	Soils	Type of plant cover	Average forage yield/kg/ha
		1. *Average annual rainfall below* 200 *mm* (range 31–535 mm)		
1.	1·1 Jaisalmer	Sandy-rocky	*Lasiurus-Cymbopogon-Aristida*	473
2.	1·2 Chandan	Sandy	*Lasiurus - Aristida- Tribulus*	424
3.	1·3 Khetolai	Gravelly	*Aristida-Cenchrus biflorus-Tribulus*	334
4.	1·4 Lawan	-do-	-do-	339
		2. *Average annual rainfall 200-300 mm* (range 50–577 mm)		
5.	2·1 Beechwal	Sandy	*Aristida-Eleusine-Lasiurus*	445
		3. *Average annual rainfall 300–400 mm*		
6.	3·1 Bhopalgarh	Gravelly	*Aristida-Eleusine-Cenchrus*	478
7.	3·2 Samdari	Deep sandy	*Aristida-Cenchrus biflorus*	905
8.	3·3 Jadan	Shallow saline	*Sporobolus-Cenchrus biflorus*	1,184
9.	3·4 Jaswantgarh	Heavy saline	*Cyperus-Sporobolus-Eleusine*	1,145
10.	3·5 Borunda	Rocky-loamy	*Cenchrus setigerus-Aristida*	1,335
		4. *Average annual rainfall above 400 mm* (range 214–840 mm)		
11.	4·1 Palsana	Deep sandy	*Cenchrus setigerus*	925
12.	4·2 Bisalpur	Shallow & rocky heavy	*Aristida-Dichanthium*	1,630

(Source : Mann and Ahuja, 1975)

grubbed out mechanically, followed by the application of the herbicide 2-4-5 T (trichlorophenoxyacetic acid) immediately after cutting away the aerial parts of the bushes (Dabadghao, 1969). Even useful top-feed species, e.g. *Zizyphus nummularia*, should not have crown over more than 14 per cent on a range if proper forage production from the pasture is desired (*Ganguli et al.*, 1964).

Top-feed-cum-shade-trees on grasslands. Trees on the rangelands provide shade for grazing animals on the range and are an important source of timber and fuel for range use. They are an important source of top-feed in the form of nutritious leaves and pods (rich in proteins and minerals) to the livestock during the lean periods of the year, thereby increasing productivity. Although forests are a source for providing top-feed in some regions, yet the area under forests under Zone 'A' (average annual rainfall below 300 mm) and Zone 'B' (average annual rainfall above 300 mm) and the over all average of the arid districts of Rajasthan is 0.4, 1.3 and 0.8 per cent respectively of the total land. The forest in western Rajasthan (arid regions) is characterized as scrub forest; and grasslands occur in plains on the lower hill slopes and on the undulating terrain in the arid parts of the State. The important grasses found in the area are *Cenchrus* species, *Lasiurus sindicus*, *Dichanthium annulatum*, *Eleusine compressa*, *Eremopogon foveolatus*, *Apluda mutica*, *Sehima nervosum*, *Aristida* species, etc.

To improve livestock production and economy at large, it is imperative to introduce some suitable top-feed tree species on rangelands to provide shade for grazing animals and the top-feed during

Table 4. Palatability ratings and chemical analysis of individual top-feed species
(Figures represent the percentages of the constituent on dry-wt. basis)

Botanical name	Common name (Local)	Palatability ratings	Crude protein	Crude fibre	Nitrogen-free extract	Ash	Phosphorus	Calcium	Magnesium
Acacia arabica Wild	*Babul*	Good	13·9	9·2	69·8	7·1	0·1	2·6	0·4
Acacia senegal Wild	*Kumat*	Moderate	10·3	9·5	65·7	16·4	0·05	6·9	0·6
Albizzia lebbek Benth.	*Siris*	Moderate	29·2	25·3	43·8	7·5	0·2	1·8	0·5
Anogeissus pendula Edgew	*Dholkra*	Moderate	7·6	19·0	65·3	8·1	0·1	3·5	0·3
Anogeissus rotundifolia	—	Moderate	8·9	20·0	62·2	8·6	0·1	3·7	0·5
Azadirachta indica A. juss.	*Neem*	Fair	12·4	11·4	66·6	9·4	0·1	3·4	0·6
Calligonum polygonoides Linn.	*Phog*	Moderate	7·4	20·7	64·2	7·6	0·1	2·4	0·8
Cassia auriculata Linn.	*Tarwad*	Poor	10·9	12·5	67·3	9·1	0·1	3·7	0·7
Grewia tenax Forsk	*Gangan*	Fair	10·3	18·9	61·1	9·5	0·1	3·8	0·5
Gymnosporia spinosa Forel	*Kankora*	Fair	9·3	19·0	63·5	8·1	0·2	1·8	0·8
Prosopis juliflora	*Bilayathi babool*	Fair	21·4	20·8	50·0	7·7	0·2	1·5	0·5
Prosopis spicigera Linn.	*Khejri*	Good	13·9	20·3	59·2	6·5	0·2	1·9	0·5
Salvadora oleoides Dene	*Pilujal*	Good	9·6	9·3	40·2	40·8	0·1	11·9*	0·7
Salvadora persica Linn.	*Kharajal*	Good	14·2	9·4	44·9	31·4	0·2	8·8	0·7
Tecomella undulata Seem	*Rohida*	Fair	12·2	15·8	63·0	8·9	0·2	3·4	0·9
Zizyphus nummularia Rox	*Bordi*	Good	11·7	16·0	65·0	7·2	0·2	1·6	0·3

* Contains free $Ca_2 So_4$

Note : Palatability ratings of "Good", "Moderate", "Fair" and "Poor" were arrived at by conducting trials with sheep, following "cafeteria technique".

(Source : Ganguli, Kaul and Nambiar, 1964) lean periods. These trees can be planted along the boundaries, inspection paths and approach roads of the compartments of the pastures in single or double rows. They will also act as wind-breaks. In addition, the trees should be planted in a staggered manner in the pasture. A good pasture may have about 30 such trees per hectare (Ahuja and Mann, 1975).

Choice of top-feed species. On the basis of the nutritent content and palatability ratings of the leaves, the order of preference of different top-feed species is as follows: *Acacia arabica*, *Prosopis spicigera*, *Salvadora oleoides*, *Zizyphus nummularia*, *Acacia senegal*, *Albizzia lebbek*, *Anogeissus rotundifolia*, *A. pendula*, *Calligonum polygonoides*, *Azadirachta indica*, *Grewia tenax*, *G. spinosa*, *Prosopis juliflora* and *Tecomella undulata* (Table 4) (Ganguli *et al.*, 1964).

Soil conservation. Grasslands generally exist on class V to class VIII lands which are subject to erosion. Soil conservation through mechanical or biological means is essential for optimized production.

Soil conservation (mechanical means). A considerable area in the Indian arid zone is rocky, with shallow soils and rolling topography. Studies were undertaken in 1961 at one of the paddocks, with the average rainfall of about 400 mm (average of 14 years) to find out suitable soil- and water-conservation measures and their effect on forage production. The soils were classified as medium loam, highly eroded, thereby exposing the rocky surface, stones and boulders. The topography was rolling with a slope of about 2 per cent. The soil-conservation treatments were as follows:

1. Contour furrows, 8 to 10 metres apart, 22.86 cm (9″) deep and 60.96 cm (2 feet) wide, forming a cross-section of 929 cm^2 (1 sq ft) were dug and the earth was excavated to form a mound on the down-slope side.
2. Contour bunds, 167.64 cm base, 15.48 cm wide at the top, 60.96 cm high, having the cross-section area of 5,574 sq. cm, were constructed at vertical intervals of 60.96 cm across the slope. One spillway of random rubble dry stone masonry, with a clear crest length of 3.05 m and a height of 30.5 cm above the ground level was constructed in each of the contour bunds to permit the excess storm water to overflow and avoid breaches.
3. Staggered contour trenches were dug at vertical intervals of 60.96 cm, having a depth of 30.5 cm and a width of 60.96 cm in section of 61 metres long across the slope with an unexcavated portion of 1.52 m to serve as a spilling section during heavy rains.

To estimate the effect of soil-conservation measures on forage production, a pair of sample plots each 22.1 m, along the slope and 3.66 m across were laid out in each of the treatments and the control plots, and were protected well. Care was taken to see that the slope, the soil type and the vegetation cover in plots under treatments and the control were identical, as far as possible. The studies were continued for ten years (1961–70). The average air-dried forage yield per hectare under different soil-conservation structures are presented in Table 5.

Soil-conservation measures increased the forage production significantly. The average increased yields, as a result of contour furrowing, contour bunding and contour trenching, were of the order of 638.7, 168.8 and 165.0 per cent respectively per year.

The distance between two successive bunds and contour trenches was greater than that in the case of contour furrows. Hence there was a more uniform spread of water in the latter, thus enhancing the soil-moisture regime, which resulted in a better growth of the grass (Ahuja *et al.*, 1973). The available soil moisture in the contour-furrowed plots was higher than that in the contour-bunded and contour-trenched plots (Murty and Mathur, 1971; Wasi Ullah *et al.*, 1972). The forage yields, therefore, were higher in the contour-furrowed plots.

In the case of lands at the foothills, the flowing *nalas* should be harnessed with

Table 5. Forage yield (kg/ha air-dried) under different soil-conservation treatments

Year	CONTOUR FURROWING Forage yield (kg/ha)			Percentage increase	CONTOUR BUNDING Forage yield (kg/ha)			Percentage increase	CONTOUR TRENCHING			Percentage increase	Rainfall in mm
	Treated	Control	Difference		Treated	Control	Difference		Treated	Control	Difference		
1961	796·2	257 0	539 2	230·2	3,220·5	83·2	2,337 3	2,689·0	724 3	257·7	466·6	131·0	544 0
1962	2,297·0	212·0	2,085·0	984·3	2,183·2	413·1	1,770·1	410 6	1,467·9	274·5	1,193 4	434·7	297·9
1963	647·6	65 5	582·1	888·4	1,546 7	288·3	1,258 4	436 4	864·2	184·5	680·0	369·1	250·4
1964	1,951·0	110 0	1,841·0	1,673·7	1,967·4	497·4	1,470 4	295·5	1,838 7	518·3	1,240·4	307·3	394·0
1965	2,293·3	234·3	1,069·0	878·7	1,716 4	1,068·4	648·2	60·6	1,549·5	906·2	643 3	70 9	477·8
1966	2,328·1	255·3	1,072 8	811·2	1,625 2	1,462·2	282 6	15·2	1,791·2	908·2	883·2	97·2	446 2
1967	1,741·0	434·3	1,306 7	360 8	1,099 7	822·2	277·6	33·7	1,286·4	866 8	418·6	49 2	789·0
1968	371·8	17 6	354·2	2,012·5	63 9	20·8	43·1	207·2	74 0	19·4	54 6	281 4	126 2
1969	—	—	—	—	—	—	—	—	—	—	—	—	119·2
1970	1,669 8	328·4	1,341·4	408·4	1,195·5	768·5	1,227 0	159·6	2,295·4	471·6	1,823·3	386·7	586 0
Mean	1,556·2	212·7	1,353·5	638·7	1,619·8	602·7	1,017·1	168·8	1,321·1	498·6	822 6	165·0	
SEm		±183·2				±196·6			±177·7				
F' Test		H. significant				H. significant			H. significant				
S.D. 5%		517 6				587·6			531 2				
1%		754·5				809·7			731·9				

Yield in 1969 was negligible owing to extreme drought (Source : Ahuja *et al.*, 1973) pucca masonry and earthen bunds across the slope to serve as water-spreading devices. Gully and *nalla*-plugging should be carried out on the rangelands.

Soil conservation on rangelands—average rainfall below 200 mm. In extremely arid regions in Lawan (Jaisalmer District), rangeland with gravelly, barren shallow soils was protected with ditch and mound fencing (about 500 m apart), in 1959; during 1961, contour furrows, each with a cross-section of 929 cm^2 and spaced 8 to 10 m apart, were constructed.

The stabilization of sand-dunes. In arid zones, shifting sand-dunes are active, except during the monsoon. They threaten the existence of nearby villages, towns and fertile lands. If stabilized and managed properly, these mobile sand masses offer a potential productive site for afforestation and grassland development (Kaul, 1968). For the stabilization and rehabilitation of the sand-dunes, four distinct processes are involved, viz. (a) protection against biotic influence, (b) the treatment of shifting sand-dunes by fixing barriers (mulches) from the crest down to the heel of the dune across the wind direction, (c) afforestation by direct sowing and or by plantings of suitable tree species, and (d) for the planting of seedlings or root slips of drought-hardy perennial tussocky grass species. In such areas, grazing should not be allowed till the dunes are stabilized. Grass may be harvested manually. The cost of stabilizing the dunes presently works out at Rs 600 to 800 per hectare (Muthana and Ahuja, 1973).

Rangelands with salinity. Vast areas in desert regions are highly saline, with a high salt concentration. If managed and utilized properly, they offer potential sites for grass production. The first step in reclaiming such land is to drain away excessive salts. Digging trenches with the dimensions of a trench being $\frac{(4' + 2')}{2}$ x 3′ or $\frac{(1.22 + 0.61)}{2}$ m × 0.914 m at a distance of about 300 metres, depending upon the slope, helps to drain away excessive salinity and salts. In such a system, grasses, e.g. *Sporobolus helvolus* (*kharada*) comes up (Ahuja and Bhimaya, 1966b). Its protein content during the flowering stage is about 9 per cent and is relished by livestock, specially cattle and sheep. It remains green for a pretty long time. It is advisable to sow or plant salt-resistant tree species, such as *Acacia nilotica*, *Prosopis juliflora*, *Tamarix articulata*, *Salvadora persica*, and *Acacia tortilis*, on the mound of the trenches to stabilize them and save them from being damaged during rains. As the reclamation of salinity progresses, the production increases, and in fairly well-leached patches, *Dichanthium annulatum* comes up luxuriantly. Such managed pastures could yield 1.0 to 1.5 tonnes of air-dried forage per hectare.

Reseeding the grasslands. A natural succession of superior species of grasses in arid and semi-arid regions is a time-consuming process. Hence reseeding with a suitable perennial grass species, having a high nutritive value and yielding high tonnage under rainfed condition, suiting different agroclimatic tracts, is the only solution. The reseeding of grasslands involves:

(a) SELECTION OF SUITABLE SPECIES FOR RESEEDING IN DIFFERENT TRACTS. *Dichanthium annulatum* gives a high yield in heavy soils, with an annual rainfall above 380 mm. *Cenchrus ciliaris* and *Cenchrus setigerus* produce high forage on well-drained soils under medium to low rainfall; *Lasiurus sindicus* gives high forage yield on sandy soils receiving low precipitation. *Pancium antidotale* performs well on well-textured soils with an annual rainfall of 250 mm and above under protected conditions; whereas *Sehima nervosum* yields good forage on the hilly terrain.

(b) RESEEDING. Owing to erratic rainfall conditions, and poor germination of seeds of *Lasiurus sindicus* and *Dichanthium annulatum*, the sowing of the mixture of seeds of *Cenchrus* species and *Lasiurus* *sindicus* and of *Cenchrus* species and *Dichanthium annulatum* is recommended for low and high-rainfall tracts respectively (Ahuja and Bhimaya, 1967). The seed-rate of different mixtures is 5 to 7 kg per hectare. The requisite quantity of unhusked seeds of grasses, suiting the tract, should be mixed with moist sandy soil three to four times the volume of seeds and drilled uniformly in lines, 75 cm apart, immediately after the first effective showers in 8-to-10-cm-deep furrows at a depth of not more than 1-3 cm under the soil.

In view of the fairly high cost involved and slow juvenile growth of high perennial grass species, it is advisable to resort to root-slip planting of grasses, e.g. *Lasiurus sindicus* and *Dichanthium annulatum*, and nurseries should be established for the purpose (Ahuja and Bhimaya, 1966b). Chakarvarty and Verma (1969) found a better establishment of the pastures of *Lasiurus sindicus* by planting seedlings than with rooted slips. But owing to water scarcity, presently the use of seedlings is not recommended.

Different strains of the above-mentioned high perennial grass species have been sorted out and their performance is under study at the substations (of the Central Arid Zone Research Institute, Jodhpur) under different agroclimatic sub-regions.

(c) WEEDING. Such reseeded rangelands need at least two weedings during their first year of establishment (Chakarvarty and Verma, 1972).

(d) PRODUCTION. The results concerning the increase in forage production due to reseeding under different condition classes of rangelands are presented in Table 6.

Table 6. The average forage yield (air-dried kg/ha) due to reseeding under different class rangelands

Year	Poor			Increase in percentage	Fair			Percentage increase
	Reseeded strip	Control	Increase (kg/ha)		Reseeded strip	Control	Increase (kg/ha)	
1960	1,066 (3)	750	316	42·1	1,173 (2)	800	373	45 4
1961	1,609 (5)	885	724	81·8	2,002 (3)	1,556	446	28 7
1962	990 (4)	692	298	30·1	1,686 (7)	869	817	94 0
1963	1,501 (2)	675	826	122 3	1,741 (6)	964	777	80 6
1964	1,552 (7)	715	837	117·1	2,516 (8)	1,213	1,303	107 3

Figures in parentheses indicate the number of trials (number of rangelands under different locations studied).

Increase in forage yield due to reseeding was from 30 to 122 per cent in 'poor' and 29 to 107 per cent in 'fair' rangeland.

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Optimum forage yield. The optimum forage yield in well-established plots of different high perennial species was studied and the results are presented in Table 7.

Yields up to 3.6, 4.7 and 9.9 tonnes per hectare were obtained from the established stands of *Lasiurus sindicus, Cench-*

rus species and *Dichanthium annulatum* (Mann and Ahuja, 1975).

Table 7. The optimum forage production (air-dry) of three high perennial grass species in reseeded strips (1960–1964).

Year	*Dry forage yield (kg/ha)* *Dichan-thium annulatum*	*Cenchrus Cenchrus*	*ciliaris setigerus*	*Lasiurus sindicus*
1960	—	—		3,600
				(4)
1961	8,894	2,596		2,250
1962	8,340	2,530		2,800
	(8)	(16)		(9)
1963	5,970	4,710		2,059
	(16)	(5)		(8)
1964	5,013	3,517		1,543
	(8)	(11)		(8)

Figures in parentheses indicate the number of rangelands studied.

(e) HILLY AND GRAVELLY TERRAIN. In hilly tracts, at the foothills and gravelly areas, reseeding is generally not a practical proposition. Such areas should be brought under the purview of the Forest Act and the State Soil Conservation Act, protected and vegetation allowed to come up.

(f) SALINE SOILS. In highly saline soils, reseeding with high perennial grass species has not given encouraging results. In rangelands with saline soils where good species fail to come up; a lower perennial, e.g. *Sporobolus helvolus*, performs well. It is quite nutritious and possesses high production potentials (Ahuja and Bhimaya, 1966b).

(g) RANGELANDS WITH CLIMAX VEGETATION. Extensive areas in the low-rainfall regions of the Jaisalmer, Bikaner and Barmer districts are covered with high-yielding nutritious grasses, e.g. *Lasiurus sindicus*. But these pasture remain underutilized owing to the shortage of potable water in the region or are subjected to over-grazing where watering facilities exist. Such vast areas are recommended to be brought under the purview of the State Forest Act or the State Soil-Conservation Act. In such areas, grazing could be regulated (1) during the monsoon when water requirements of domesticated animals are lower and some run-off water is available in open ponds for animals and livestock-owners, (2) by dividing the area into suitable blocks for practising rotational grazing.

Fertilization. The nutrient content and production potentials of forage species on the rangelands in western India is quite high (crude protein, about 7 to 12 per cent, Mann and Ahuja, 1975). For optimized production, it is essential to provide adequate nutrients in the soil, more so because the rangelands are highly depleted of soil nutrients and are subjected to erosion hazards. The application of farmyard manure to vast areas of grasslands, forest lands, fallows, etc. is too costly and is not a practical proposition. Desert soils of Rajasthan are generally not deficient in potash, but they are, however, deficient in nitrogen. The broadcasting of nitrogenous and phosphatic fertilizers has not given tangible results. The placement of fertilizers, e.g. sulphate of ammonia, urea and superphosphate, have given encouraging results. The application of sulphate of ammonia at 113 kg/ha (20 lb nitrogen per acre) has resulted in increased yields of forage by 50 to 70 per cent over their respective controls during the years of normal rainfall. The increase in the air-dried forage yield due to fertilization is of the order of 460 to 1,912 kg/ha. The protein content of forage on fertilized pastures was higher than that in the control plots (Ahuja, 1975).

In areas with annual rainfall of 300 mm and below, fertilization with 20 kg of nitrogen per hectare in the form of ammonium sulphate or urea, through placement in the soil, is recommended. In areas with the annual rainfall above 300 mm, a dose of 40 kg/ha of nitrogen per hectare is recommended. In gravelly soils, the application of fertilizer is not recommended for the present (Ahuja, 1975).

The role of legumes on rangelands. As the availability of fertilizers is a problem and their cost is quite high, the role of legumes on grassland production is under study. In limited trials, legumes, in combination with cultivated pastures, have resulted in a higher forage yield with higher nutrient (specially crude protein) content in the composite forage material. Studies on the compatability and performance of promising legumes, e.g. *Dolichos lablab*, *Phaseolus atropurpureus*, *Clitoria ternatea*, *Rhyncosia minima*, *Atylosia scarabaeoides*, *Cyamopsis tetragonoloba*, *Phaseolus aurea*, *P. aconitifolius* and *Vigna sinensis*, on grasslands under different agroclimatic sub-regions are in progress. In areas, e.g. the Bikaner District, in pure stands of *Lasiurus sindicus*, legumes, e.g. *Phaseolus aconitifolius* (*moth*) is taken as an interspace crop. It improves production and adds to the resultant product (Ahuja, 1975).

Provision for drinking-water on rangelands

No range-management programme will be successful unless adequate arrangements for drinking-water for animals and workers are made. In the interior of the desert, water is one of the main limiting factors for the proper utilization of rangelands and livestock production. Vast stretches of grasslands under the climax to sub-climax cover of *Lasiurus sindicus* (*sewan*) remain underutilized owing to the non-availability of drinking-water. Till some permanent arrangement for water-supply is made, it will be advisable to provide underground water, reservoirs (tankas) for livestock and human consumption on the range (Prajapati *et al.*, 1973).

A 'tanka' with a capacity of 200 kilolitres is sufficient for 100 hectares of "Good" condition class rangeland; but it would also suffice for 200 hectares of rangeland in areas where the seasonal grazing during the monsoon is to be practised owing to acute water scarcity (Ahuja and Bhimaya, 1967).

Utilization. The utilization of forage from grasslands can be through (a) harvesting, preserving and then feeding it to the livestock, (b) grazing.

Grazing saves the cost of harvesting of low-set and low-yielding grass species. Livestock, while grazing, work up the soils with their hooves, break up the top crust of the soil, thereby encouraging a better percolation of water for plant use and better range production. Their excrements, i.e. dung and urine, add to the plant nutrient contents of the soil and improve its fertility.

The palatability of different species of grasses and the grazing behaviour of animals

On the rangeland, various types of plant species come up. Their growing habits, morphological and physiological characteristics differ considerably, and they affect their utilization by different species of farm animals. Among all grasses, *Cenchrus ciliaris* and *Cenchrus setigerus*, the perennial species, are most palatable to all species of farm animals during the entire year. The annual species, such as *Aristida funiculata* and *Cenchrus biflorus*, on maturity cause servere discomfort to sheep from the middle of August to the beginning of November, as their awns and burrs pierce through the mouthparts and the skin of the grazing animals. Such species are also troublesome to cattle. During this period, perennial species, such as *Dichanthium annulatum* and *Lasiurus sindicus*, are relished most. From November onwards, these perennial species become woody. Then they are not liked by cattle and cause discomfort to sheep by injuring their mouthparts with the sharp ends of the stems. Therefore the annuals whose burrs and awns have been shed are relished. From March onwards, when the annual grasses get exhausted, the high perennials get broken down and are eaten. Details have been discussed by Ahuja (1971). During the hot weather, animals are crazy after greens. Cattle eat the green shoots of *Calligonum polygonoides*, *Capparis aphylla*, *Aerva pseudotomentosa*, etc. *Tribulus terrestris* is poisonous to cattle, whereas it is nutritive for sheep. *Fagonia cretica* and *Blepharis* sp. are palatable to sheep, but are not palatable to cattle. Owing to the thorny nature of some plant species, e.g. *Lycium barbarum*, *Balanites aegyptiaca* and *Mimosa hamata*, they are harmful to cattle on the range, but their leaves are eaten mostly by goats and to some extent by sheep. Tussocky grasses, e.g. *Dichanthium annulatum* and *Lasiurus sindicus* during maturity, are unpalatable to sheep and goats, but are grazed upon by cattle. Low-set grasses, such as *Oropetium thomaeum* and the species of *Enneapogon*, can be grazed by sheep only. To have the best utilization of rangeland production, it is best that sheep and goats follow cattle—the goats will eat up thorny bushes, which otherwise are troublesome to cattle.

Suitable species of farm animals for grazing on different types of rangelands. Different species of farm animals utilize different plant species, depending upon their chemical composition, growth, morphological, physiological and other characteristics. A rangeland infested with bushes and thorny vegetation can be used by goats. Low-set plant species are used well by sheep. Tussocky grasses, such as *Lasiurus sindicus*, *Dichanthium annulatum* and *Panicum antidotale*, are better used by large animals, e.g. cattle. Hence the choice of introducing farm animals on the range depends upon the botanical composition of the latter.

Preservation of forage

Specially in the arid regions, there is an acute shortage of forage from November onwards when the rangelands get grazed. The supply of fodder during dry months is a problem, except in irrigated areas. To have a regular supply of good and nutritious forage, it is essential to process and preserve it under proper condition. Forage can be preserved by making hay or silage.

Hay-making. Materials from rangelands which are most suitable for hay-making are perennial grasses, viz. *Lasiurus sindicus*, *Cenchrus ciliaris*, *C. setigerus*, *Panicum antidotale*, *Dichanthium annulatum*, and tall high-yielding annual grass species and legumes.

To have optimum nutrients in the cured forage (hay), the plants should be harvested at the pre-flowering to flowering stage in the morning hours after the dew has dried up. Hay-making reduces moisture in the green forage through drying or dehydrating. Hay-making should be quick, as far as possible, so as to have the maximum nutrient content, including carotene, in the resultant product.

The developmental cost and expected returns from rangeland development

The cost of upgrading rangeland depends on the locality, the land form, the availability of potable water, the size of the block, etc. The estimated cost of upgrading the rangeland under denuded conditions through fencing, soil and water conservation, if necessary, the reseeding, provision of stock water, etc. (based on a 1,000-hectare block) works out at Rs 500 to 1,400 per hectare, depending upon the land form, locality, etc. (Ahuja, 1975).

The needs of livestock and dairy products will continually increase owing to the increasing human population. The increasing of livestock feeds and fodders

Table 8. Livestock population and forage budget in the arid districts of Rajasthan

Year	Adult cattle unit (ACU)	Forage in million tonnes			Forage shortage %
		Needs	Availability	Shortage	
1975	6·733	16·833	10·169	6·664	39·6
1980	7·405	18·571	11·693	6 824	36·8
1985	8·146	20·366	13·316	7.050	34·6
1990	8·961	22·400	15·466	6·934	30·9
1995	9·858	24·645	17·785	6·860	27·8
2000	10·834	27·085	20·159	6·626	23·8

will have to be phased. Assuming a yearly increase in livestock population at 2 per cent and the forage production at 3%, and 2 years out of five years as scarcity years in the arid regions, the forage production from all sources and its budget are presented in Table 8.

In the light of the continued shortage of fodder for livestock, it is essential to improve and upgrade the existing rangelands speedily and use them rationally to improve the economy.

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23

CROP PRODUCTION IN THE INDIAN ARID ZONE

H. S. MANN AND R.P. SINGH

DESPITE water scarcity being a limiting factor in crop production, about 45 per cent of the total land area (3.2 lakh km^2) of the Indian arid zone is sown to crops annually. More than 85 per cent of the cultivated area is rainfed and is subject to the vagaries of the monsoon. Estimates are that even if all the irrigation potential is achieved by the turn of this century, a sizeable portion of the cultivated land in the arid regions of Rajasthan, Gujarat, Haryana, Punjab, Andhra Pradesh and Karnataka will continue to be rainfed. For instance, in the arid zone of Rajasthan, comprising about 60 per cent of the Indian arid zone, the total area to be irrigated by the Rajasthan Canal and other groundwater resources will be about 11 per cent. Thus the remaining 89 per cent of the region will ultimately remain such that farmers will have to learn to live better with natural rainfall as the major source of water. The problems of rainfed agriculture should, therefore, receive due attention of scientists and planners.

Crop production in the rainfed areas, in general, and in the arid regions, in particular, is unstable and risky, leading to low and unremunerative yield levels. *Bajra* (*Pennisetum typhoides*), *kharif* pulses, *jowar* (*Sorghum vulgare*) and sesamum are the principal crops grown.

THE PROBLEM

An analysis of the problems of crop production in the rainfed areas of the Indian arid zone reveals that an acute ecological imbalance of the components of productivity is responsible for limiting the consistency of a remunerative crop production in these regions. Harsh and unfavourable climatic conditions, coupled with wind-blown soils low in organic matter and poor in moisture retention are responsible for a sparse vegetative cover and low unstable yields of dryland crops. For example, in western Rajasthan, the problems imposed by low annual precipitation (366 mm) are accentuated by its frequent erratic distribution from season to season, a high solar incidence of 450 to 500 calories per cm^2 per day and a wind velocity of 10 to 20 km per hour resulting in high P.E.T. (6 mm/day) and a consequent high mean aridity index of 78 per cent. Soils are mostly sandy, with a low organic matter content (0.1 to 0.45 per cent) and with a poor moisture-holding capacity (25 to 28 per cent) and a high infiltration rate of 9 cm/hour. Soil salinity and alkalinity to the extent of 45 per cent of the unirrigated area and the surface crust-formation after *kharif* sowing, following light showers, complicate the situation (Singh *et al.*, 1974).

Although the conventional dryland crops, viz. pearl-millet or *bajra* (*Pennisetum typhoides*), sesamum and *kharif* pulses, particularly *mung* (*Vigna radiata*), *guar* (*Cyamopsis tetragonoloba*) and *moth* (*Phaseolus aconitifolius*) are adapted to the existing conditions of low soil fertility and moisture stress, the local varieties offer a limited choice for increasing crop production under varying rainfall situations.

THE EXISTING SITUATION

An analysis of the rainfall data from 1901 onwards reveals that the western parts of Rajasthan, representing about 60 per cent of the Indian arid zone, have (i) normal (350—400mm) and (ii) good rainfall (>400 mm) years occurring in one out of two years (48 per cent probability) which are to be capitalized through improved yield plateaus to tide over the lean years (52 per cent probability). One interesting point that emerges from the rainfall distribution during the past 75 years (1901-1975) is that 20 of these normal and good-rainfall years have been quite favourable even for double cropping in drylands (Anonymous, 1976 a).

Situations, such as the early onset of the monsoon (occurring in one out of three seasons), and the late onset of adequate rains (possible in one out of 4 years) call for adequate and advance preparations. Also, proper management practices for situations of prolonged drought (3 to 4 weeks) occurring at the seedling stage (during July) in one out of five years (20 per cent probability) and at flowering and grain-formation stages (August and the first fortnight of September), possible in two out of five years (40 per cent probability) form an essential part in combating drought and stabilizing crop production on drylands of western Rajasthan.

In good-rainfall years, the moisture losses under run-off and deep drainage taken together reach as high as 40 per cent of the seasonal rainfall, each accounting for almost half of the total losses. It has been estimated that the moisture availability of the order of 284, 214, 173 and 124 mm could be obtained during the cropping seasons experiencing good (>400 mm), normal (350-400 mm), below-normal (250-350 mm) and poor (>250 mm) rainfall (Anonymous, 1976 a).

The existing cropping patterns on the rainfed lands are traditional and subsistence-oriented. The following analysis of the cause-and-effect relationship will help us to understand the predominant maladies afflicting crop production in these regions:

Causes	*Effects*
(a) Lack of moisture and restricted period of moistute availability	(i) Restricted choice of crops and varieties (ii) Low cropping intensity (iii) Inefficient utilization of inputs
(b) Lack of crops and varieties fitting into the existing rainfall pattern, appropriate soil-and-moisture-conservation measures, fertilizer use and plant protection.	(i) Low and unstable crop yields
(c) The removal of natural vegetation as a result of uncontrolled grazing, the felling of trees and shrubs for fuel	(i) Inadequate vegetative cover, leading to a large-scale soil and nutrient loss due to wind erosion
(d) Pressure of population	(i) The extension of cultivation to marginal and sub-marginal lands, leading to low productivity on the one hand and a greater risk of soil erosion on the other

It thus appears that the lack of adequate vegetative cover, leading to devastating wind erosion, is the primary malady responsible for upsetting the ecological balance of this region.

THE APPROACH

The amelioration of arid regions falling in the rainfall range of 300 mm and below can be best achieved by a large-scale afforestation with suitable species of trees and by developing a grass cover by growing adapted species of grasses. Crop production in such regions should be discouraged. Animal husbandry backed up by range-land management and forestry should be the mainstay in these regions. In the transition belts, with an annual precipitation ranging from 300–400 mm, an integration of crop husbandry and animal husbandry should go together for stabilized production (Singh and Prasad, 1975). The National Commission on Agriculture has also laid emphasis on animal husbandry-orièntated programmes for improving the economy of such regions.

In areas receiving 400 mm of rainfall and above technology for dryland crop production should be adopted for improving and stabilizing crop yields. In order to make crop production a remunerative enterprise in these areas, the following measures should be adopted:

(a) Selection of crops and varieties having growth patterns matching the rainfall pattern and possessing higher moisture-use efficiency
(b) Selection of suitable crops and varieties for conditions of delayed onset of the monsoon and other weather aberrations
(c) The adjustment of sowing time so as to ensure that the periods of flowering and grain-filling coincide with the periods of adequate moisture availability
(d) Tillage practices conducive to good seed-bed preparation without much loss of soil, moisture and nutrients. Techniques ensuring a proper placement of seed and fertilizers in the moist zone, leading to optimum crop stands
(e) A judicious fertilizer use commensurate with the status of soil nutrient needs of crops, plant population and available soil moisture
(f) The adoption of appropriate water-harvesting techniques so as to ensure higher amounts of moisture for longer periods
(g) The conservation of moisture through the use of partial or complete sub-surface moisture barriers and organic mulches to cut down losses owing to deep percolation and evaporation respectively
(h) A timely control of weeds and the adoption of effective plant-protection measures
(i) The harvesting of crops of appropriate cropping systems so as to impart stability in years of subnormal rainfall and to increase production in years of normal and above-normal rainfall

Three basic approaches are suggested to cope with the problem of instability in crop production in the rainfed areas of the arid zone. These are: crop diversification, intercropping systems and the recycling of run-off water in the event of prolonged drought or supplemental irrigation (Singh, 1976). Castor and *guar*, among dryland crops, and *Cenchrus ciliaris* among perennial forage crops, have been found to result in the stability of agricultural production on rainfed lands. *Bajra* (pearl-millet) remains the most unstable crop among cereals. In view of the fact that it occupies about 60 per cent of the cultivated area in the rainfed areas of Rajasthan, and is the staple food of millions of dryland farmers, efforts have to be directed towards the stabilization of its production. Transplanting, although labour-intensive, is a surer technique by which reasonably good yields can be obtained even in years of low or subnormal rainfall. In 1974 (with 136 mm of rainfall), whereas the direct-seeded crop of *bajra* failed, the transplanting of 20 to 25-day-old seedlings resulted in 7 q of grain yield/ha (Anonymous, 1974). In good-rainfall years also, the transplanting of 24-day-old seedlings of *bajra* (BJ104) resulted in more than 30 per cent increase in grain yield over the direct-seeded crop (18.6 q/ha) planted in the third week of July (Anonymous, 1976 b).

SELECTION OF CROPS AND VARIETIES MATCHING THE RAINFALL PATTERN

It appears that owing to inadequate efforts to dovetail the plant-breeding programmes with other improvements in dryland agriculture in the past, the individual practices developed by the scientists for moisture and soil conservation have not found wide adoption because of their marginal impact on productivity. High-yielding varieties of crops developed have given a silver lining to the otherwise dark picture of rainfed agriculture. Despite their excellent yield potentials and favourable developmental and maturity patterns, these crop varieties need modification to conform to the prevailing climatic conditions. To obtain a consistently high level of production, crop varieties to be grown on drylands should possess a considerable degree of tolerance to drought, should mature early and have high yield potentials. Keeping these objectives in view, high-yielding varieties of cereals, pulses and oilseeds have been developed. They are: crops and varieties, apart from NHB3 of *bajra*, S8 and M8 (mutant of RS4) of *mung*, FS68 of cowpeas, Var4-2 and T13 of sesamum, 2470(12), 4210(26) and KVS-1 of *guar*, Aruna, CH3 and R63 of castor and EC68414 and EC69874 of sunflower (Anonymous, 1976 a). It has been found that whereas crops, such as pearl-millet and sesamum, failed totally owing to the late onset of the monsoon, crops such as *mung*, cowpeas, castor and sunflower, gave remunerative yields.

ADJUSTMENT OF SOWING TIME

The sowing time of *kharif* crops has to be so adjusted that flowering and fruiting which are considered to be most crucial, coincide with the periods of adequate moisture availability in the soil profile. For *kharif* crops, this period falls in the third and fourth weeks of August in western Rajasthan. As such, the appropriate sowing time would be the last week of June to the first week of July, when the probability of receiving showers (30 to 40 mm) is usually high. Considering the staple dryland crops, viz. *bajra*, its sowing after the second or third week of July invariably results in either poor yield or total failure. Therefore, under the delayed onset of the monsoon, nursery-sowing and transplanting of *bajra* are recommended.

TILLAGE AND SEEDING PRACTICES CONDUCIVE TO GOOD CROP STANDS

Inadequate crop stands constitute one of the major reasons for low crop yields on drylands. An ideal tillage practice should result in a uniform initial stand, maximum weed control and should also result in the coverage of large areas during the restricted sowing period. One sub-surface cultivation with a sweep cultivator coinciding with the onset of the monsoon and again once before sowing was found to result in a higher grain yield of *bajra*. Almost a complete control of the weed (*Cyperus rotundus*) was achieved with seed-bed preparation, using a heavy-duty mouldboard plough (Plate II).

For obtaining a uniform crop stand, it is necessary that the seed is placed at the proper depth in relation to its size and soil moisture and is uniformly distributed. Sowing with a drill having hoe-type furrow-openers and on the row-press wheels has been found to result in a uniform stand leading to a higher grain yield of *bajra* than when it is sown with disc-type furrow-openers. Post-sowing compaction results in a higher coefficient of the rate of seedling emergence, which at times is very important on drylands.

JUDICIOUS FERTILIZER USE

Fertilizer use on drylands has almost been non-existent, mainly owing to uncertain rainfall and the cultivation of non-responsive crop varieties. As such, the earlier belief of the dryland farmers that fertilizer application was injurious to dryland crops was justified. With the availability of fertilizer-responsive varieties of dryland crops and the knowledge gained on the quantity, time and method of nutrient application, a judicious fertilizer use can offer enormous possibilities of increasing dryland crop production under normal and above-normal rainfall situations and stabilizing them in years of subnormal rainfall. Appropriate fertilizer-use technology will assume greater importance in double-cropping systems found to be feasible in years of high rainfall occurring in 20 out of 75 years. Researches carried out so far on fertilizer use on drylands have clearly indicated the beneficial effects of optimum nutrient application to most of the crops. For instance, experiments conducted at the Central Arid Zone Research Institute, Jodhpur, have indicated that yield increases of the order of 35 to 150 per cent in the case of pearl-millet, 150 to 190 per cent in the case of sorghum, 22 to 100 per cent in the case of green gram, 11 to 77 per cent in the case of sunflower and 180 per cent in the case of sesamum in good-rainfall years were obtained with the application of 40 kg of N and 40 kg of P_2O_5, and 60 kg of N and 40 kg of P_2O_5, 15 kg of N and 40 kg of P_2O_5, 40 kg of N and 40 kg of P_2O_5 and 40 kg of N and 40 kg of P_2O_5 per hectare respectively. The response of pearl-millet and sunflower to nitrogen application was the highest, 10.2 and 7.0 kg/kg N, at 40 and 30 kg nitrogen levels respectively. In the case of forage grasses, *Cenchrus setigerus* and *Panicum antidotale* responded favourably to fertilizer use in the drought year (1974) also, the response being of the order of 44.7 to 55.3 kg of green forage/kg/N hectare. In the normal-rainfall years (1971 and 1972), the response of *C. setigerus* to fertilizer nitrogen ranged from 55 to 62 kg of green forage/kg N; whereas in the case of *P. antidotale*, the response ranged from 97 to 203.3 kg/kg N. Thus, irrespective of the quantum and distribution of rainfall fertilizer use was found to be beneficial in the case of forage grasses (Anonymous, 1976 a).

An idea of additional yields and net returns due to fertilizer use in the case of cereals, grain legumes, oilseeds crops and forage grasses can be had from the data presented in Table 1. It is evident that high net returns of the order of Rs 2,700 to Rs 3,260 per hectare can be obtained as the result of fertilizer use in the case of cereal crops, e.g. pearl-millet and sorghum in years of good rainfall.

The efficiency of fertilizer use can be enhanced manifold by placing the fertilizer 5 to 10 cm below the seeds in the moist zone at the time of sowing. Further economy in fertilizer use can be effected by withholding a part of nitrogen, which can be applied when moisture becomes available at an appropriate stage of development. In case moisture is scanty, the application of the second dose of nitrogen can be withheld, thereby bringing about a saving in fertilizer use.

The beneficial effects of Fe, Zn, Mg and a mixture of all trace elements had been exhibited well over the control in a four-year study at Jodhpur (Misra, 1961). The mean percentage increases in the grain yield of *bajra* were 21.6, 18, 15 and 5.4 due to Fe, Zn. Mg and a mixture of all trace elements and Mn respectively.

WATER-HARVESTING SYSTEMS

Owing to low rainfall and its erratic distribution, the dryland crops encounter drought during critical growth periods, leading to low yields or to the total failure of crops. This problem can be overcome to a great extent by adopting an appropriate water-harvesting system which can provide for additional quantities of moisture. For the situations obtainable in the rainfed areas of the arid zone, two water-harvesting systems, viz. inter-plot and inter-row systems, have been found to offer opportunities for *in situ* water-harvesting. Studies at the Central Arid Zone Research Institute, Jodhpur, have shown that the total production by cropping only two-thirds of the field (leaving one-third for micro-catchment) by adopting the run-off farming is the same as obtained from conventional cropping on a flat surface. The run-off farming has been found to offer potentialities for increasing and stabilizing yields, thereby lowering the risk of crop failure and saving inputs required for crop production (Anonymous, 1976c) However, in case no land is to be sacrificed for water-harvesting as catchment, the inter-row system of water-harvesting is more practicable than the inter-plot water-harvesting system. The modified inter-row water-harvesting system (MIRWHS) developed at the Central Arid Zone Research Institute induces an additional run-off in the trenches from the ridges and also from the micro-catchments provided in-between the trenches. There was 13.4 per cent more moisture in the soil profile under this system than under the flat system at the time of harvesting the *bajra* crop—a distinct advatnage conferred on the yield of succeeding crop. Recent studies have shown that there was a lower weed population in the case of the modified inter-row water-harvesting system than in the case of the flat and inter-row water-harvesting systems.

In the drought-prone areas, it may not only be feasible but desirable to set apart a portion of the land for water-harvesting and provide for a pond or a tank to collect and store the run-off water. The stored water can be applied to the standing crops nearby as a life-saving device during periods of prolonged drought either at the seeedling stage or at the grain-filling stage of the cereal crops. A good rainfall distribution during the cropping season, in some years, may not warrant the use of stored water for supplemental irrigation. In that event, the stored water can be used to provide a supplemental irrigation for long-duration crops, e.g. cluster-bean and castor. The recycling procedure can also be used with advantage for giving one pre-sowing irrigation to supplement the moisture stored in the soil for raising two crops on the same field in the above-normal monsoon years.

SOIL- AND MOISTURE-CONSERVATION MEASURES

Soil- and moisture-conservation programme is basic to any programme of crop-production in the rainfed areas. In the past, increased agricultural production as a result of soil- and moisture-conservation measures has been of the order of 15 to 50 per cent, which itself is low primarily because of the limitations of the biological material responsive to the environment. The reorientation of the soil- and moisture-conservation programme and its linkage with plant material and package of practices has been suggested for increasing agricultural production in the rainfed areas of the country. In the arid zone, contour-farming is, no doubt, vital from the point of view of soil and moisture conservation. More significant, however, is the wind action which may particularly be serious during summer. Stubble-mulching and wind strip-cropping are the basic remedies for the maladies caused by the action of wind. Misra (1964) reported that: (i) soil loss due to wind erosion increased with the decrease in the size of the stubble of pearl-millet left at the time of harvesting, the minimum (761 kg/ha) and the maximum (2,088 kg/ha) having been recorded in the case of whole stubble and control plots respectively. A stubble height of 15 cm was found to be the optimum, both from the point of view of fodder yield and wind-erosion control; (ii) in studies on wind strip-cropping, the average yields of 272 kg and 257 kg per hectare of *Phaseolus radiatus* (now renamed *Vigna radiata*) and *Phaseolus aconitifolius* respectively obtained under unprotected plots increased to 484 kg and 372 kg per hectare respectively, when the cropped strips were protected by perennial protective strips of *Lasiurus sindicus* and *Ricinus communis*, established at right angles to the general direction of the prevailing winds. Soil moisture in the protected cropped land was found to be higher (0.5 to 1.5 per cent) than that in the unprotected land.

One of the basic principles of wind-erosion control is to keep a reasonable plant cover of the soil surface to reduce the action of the wind. An analysis of the rainfall data of Jodhpur for 75 years (1901–1975) has revealed that the pattern of rainfall distribution during 20 years has

Table 1. Additional yields and net returns due to fertilizer use in a good-rainfall year

Crops	Additional yield (q/ha)		Gross returns (Rs/ha)	Cost of fertilizer + application cost (Rs/ha)	Net returns (Rs/ha)	Returns (Rs) per rupee invested
	Grain	Straw				
A. Cereals						
1. Pearl-millet	26 0	95·6	2,878·4	182·0	2,696·9	15 82
2. Sorghum	30·6	49·6	3,487·9	227 0	3,260·9	15·37
B. Grain legumes						
1. Green gram	2·1	11·2	654 5	159·5	495 0	4 10
2. Cluster-bean (*guar*)	1·2	8·4	248 4	159·5	88·9	1·56
C. Oilseeds						
1. Sunflower	2·0	—	710·0	182·0	528·0	3·90
2. Sesamum	5·6	11·5	2,034 0	136·0	1,898·0	14·95
D. Forage grasses (fresh forage)						
1. *Cenchrus ciliaris*	—	190·0	1,900 0	136·5	1,763·5	13·91
2. *Panicum antidotale*	—	156·0	1,560	136 5	1,423·5	11·42

Table 2. Yield of *tinda* (q/ha) as affected by the sub-surface moisture barrier (bentonite clay)

Treatments	Yield of *tinda* in q/ha				Mean yield (q/ha)	Percentage increase in yield over that in the absence of the barrier
	1973	1974	1975	1976		
1. No barrier	110	17	78	57	65	—
2. Moisture barrier (bentonite clay placed 75 cm deep)	160	33	93	66	88	35

Table 3. The yield of *tinda* (q/ha) as influenced by the run-off concentration and the barrier in a low-rainfall year—1974

Treatments		With microcatchments		Flat
Barrier		43·1		19·7
Barrier + *bajra* husk mulch		45·1		23·8
Mulch only		22·1		14·2
Control		18·2		13·4
	'F' Test	SE. m±	CD 5%	CD 1%
Run-off	NS	2·52	—	—
Barrier and mulch	Sig.	2·71	8·34	11·7
Run-off × barrier	NS	3·83	—	—

been quite favourable to a double-cropping system which can be followed with advantage on drylands. In *kharif* 1975 (rainfall, 560 mm), it was demonstrated that 9.5 q/ha of *raya* (*Brassica juncea*) and 7.3 q/ha of safflower could be obtained on the residual soil moisture after harvesting *bajra* (pearl-millet) and *mung*, the yields of *bajra* and *mung* being 32 q and 8 q/ha respectively. Thus the emphasis should be to keep the land covered as long as possible. However, under this system of conservation-cum-production farming, the tillage should be minimum and the use of heavy disc implements should generally be avoided. Sweep tillers, rod-weeders and wide-blade cultivators are the ideal tools for use in areas prone to wind erosion.

In an experiment conducted recently, a 1-metre-wide strip of *bajra* (pearl-millet) planted as a shelter barrier against the prevailing wind direction reduced the wind speed by 63 per cent in the cropped area under cowpeas and lady's-finger. Also the *bajra* shelter barrier increased the yields by 190 per cent and 90 per cent in the case of lady's-finger and cowpeas respectively (Anonymous, 1975).

In the arid zone, having sandy soils, surface evaporation is as important as deep percolation, for once the surface soil (which is mostly sand to loamy sand) dries up, it acts as a natural mulch against the loss of moisture through evaporation. Nevertheless, the drying of the surface soil quickly and the excessive evaporation just after rainfall pose problems in seedling emergence and proper crop establishment, if there occurs a spell of drought after sowing or during the establishment stage when the root-zone is restricted to a soil depth of 15 to 20 cm from the surface. Under such conditions, the use of surface mulches is advantageous in delaying the drying of the soil surface.

To cut down losses owing to deep percolation, a technique of partial moisture barrier (bentonite clay) incorporation has been developed at the Central Arid Zone Research Institute, Jodhpur. The placement of a bentonite barrier 75 cm deep in pits gave an yield of 160 q/ha of *tinda* (*Citrullus vulgaris* var. *fistulosus*) against 110 q/ha obtained from the control (no barrier) in 1973 which was a good-rainfall year—a rainfall of 544 mm having been recorded during the *kharif* season. Considering the performance of *tinda* with and without barrier over a period of 4 years, it was observed that the use of the barrier resulted in 35 per cent increase in the yield of the vegetable over that in the absence of the barrier (Table 2).

It has now been shown that the technique works very well when the barrier and run-off concentration systems are combined. In the low-rainfall years, the incorporation of the barrier alone may not help to increase the storage of moisture in the soil. It is only in combination with a run-off concentration system that the storage of soil moisture increased by 20 to 25 per cent during different rainy spells. In a low-rainfall year (136 mm), the run-off concentration (with micro-catchment) in combination with a sub-surface barrier of bentonite clay resulted in 43 q/ha vegetable yield against 19.7 and 13.4 q/ha on a flat system with and without barrier respectively (Table 3).

The use of organic mulches, such as *bajra* husk, wheat straw and grass mulch, helped to maintain a high moisture regime in the soil profile (for more than 30 days after application) and a uniform thermal regime conducive to plant growth in the soil-surface zone.

TIMELY WEED CONTROL

Weeds compete with crops for both moisture and nutrients. The timely control of weeds, as such, assumes great importance in the rainfed areas, it should therefore, be restored to within the first 30 days in the case of pearl-millet and within 20 days in the case of *mung*. Weed control thereafter is of little or no use, as the damage already done is irreversible. However, the weeds should not be disturbed on lands lying fallow during *rabi* until the first shower which generally comes sometime in the second half of June. Here, a compromise has to be made between the conservation of soil fertility and soil as such. Obviously, soil conservation is the prime consideration, because fertility can be restored if there is soil, but soil once lost cannot be brought back. Moreover, if the weeds are incorporated into the soil with inversion ploughing, the nutrients they extract are brought back to the soil and may be available to the succeeding crop certainly at a later stage, may be in the next season.

FARMING SYSTEMS FOR DRYLANDS

To ameliorate the problem of low and unstable crop production in the rainfed lands of the Indian arid zone, steps for stabilizing and increasing yields of dryland crops will have to be taken. Any technology developed for these regions should be able to impart stability in years of sub-normal rainfall, increase production in years of normal and above-normal rainfall. The role of crop diversification in stabilizing production on drylands has already been stressed. The intercropping of annual grain legumes in perennial grasses is yet another tool which can be capitalized on for stabilizing production.

(i) *Intercropping system for drylands.* Grasses are important in an arid zone from various aspects, viz. soil improvement, animal feed and soil conservation against wind erosion. Legumes can be grown with advantage as intercrops with grasses, the former benefiting from the improved physical condition of the soil induced by the grass sod and the latter utilizing the improved fertility conditions resulting from the fixation of nitrogen by the legumes. Also in the event of failure of rains, grasses may give a reasonable yield to avert a complete failure of crop. For instance, in 1974, with 136 mm of *kharif* rainfall, though the legume crops failed, grass (*C. ciliaris*). as the base crop gave a yield of 49 q/ha as green fodder (Anonymous, 1974). On the other hand in 1975, which was a year of very good rainfall (650 mm), the yield of *guar* (cluster-bean) grain grown as an intercrop was 15 q/ha, with a forage yield of 108 q/ha from the base crop of *Cenchrus ciliaris* (Anonymous, 1975).

(ii) *The use of non-monetary inputs in dryland agriculture.* The importance of non-monetary inputs for a small farmer engaged in dryland agriculture needs no emphasis. For instance, simple practices, e.g. the soaking of seeds in water and growing crops in the paired-row system, have been found to result in good crop establishment and higher yields. The soaking of seeds of sunflower, safflower and castor in water for 24 hours before sowing has been found to result in early seedling emergence and a good crop stand. Five cm as the depth sowing for sunflower and safflower and 15 cm for castor have been found to be optimum (Anonymous, 1976a). Such depths may be important in areas where a quick drying-out of the upper soil layer after sowing takes place and where the establishment of crops is a problem. Similarly, a paired-row system of planting has been found to result in higher yields and a better moisture-use efficiency than a uniform system of planting in years of low and normal rainfall in the case of *bajra*, grain legumes and *Cenchrus ciliaris*. Recent experiments carried out on the systems of planting have shown that growing one row of pearl-millet in the paired- and triple-row system of planting *mung* led to 2 to 2½ times more productivity than the planting of *mung* according to the above systems. The yield of the principal crop (*mung*) is no doubt reduced (by about 50 per cent) under the intercropping systems, but the decline in the yield is more than compensated for much higher total productivity, the major share being contributed by the companion crop (pearl-millet). For obtaining-higher productivity per unit area per unit time, therefore, the planting of one row of pearl-millet in the inter-row spaces of *mung* may be rewarding. Recent studies have further revealed that the yield of *bajra* grain is appreciably reduced (62 per cent), if it is taken in the *bajra-bajra* rotation as compared with the *mung-bajra* rotation. *Bajra* taken after *mung* inoculated with the appropriate *Rhizobium* culture in the previous year resulted in the same yield level as that obtained after the uninoculated *mung* fertilised with 40 kg of P_2O_5 per hectare (Anonymous, 1976). Inoculation of the seeds of legumes can bring about a great saving in the use of fertilizers.

GAPS IN KNOWLEDGE AND THE FUTURE LINES OF WORK

Much valuable work has been done to stabilize and increase crop production on the rainfed land of the arid zone. However, there are many gaps in our present-day knowledge pertaining to rainfed agriculture. Some of the gaps are listed below:

(a) Knowledge regarding the plant types for intercropping and managing intercropping systems in relation to nutritional parameters and radiant energy;
(b) tillage in relation to soil and nutrient conservation crop establishment;
(c) organic recycling; and
(d) run-off collection and its recycling.

Basic knowledge on the following points is still lacking:

(a) The crusting of soil and its control;
(b) the soil-water-plant relationships in respect of moisture stress;
(c) the movement of moisture in arid-zone soils; and
(d) water balance, as influenced by different management conditions.

More research efforts have to be made to realize the yield potentials of legumes. These efforts will encompass the tailoring of suitable varieties in the case of neglected crops, e.g. *moth* and *guar* and the nutritional requirements of legumes, especially in respect of phosphorus. Fodder and forage agronomy has not received the attention it deserves and more work needs to be done before fodders and forage can become popular with the farmers. Suitable farming systems integrating various aspects of dryland crop production with sylvi-pastoral management and with due regard to soil productivity and ecological balance have to be evolved for sustained productivity of the arid-zone ecosystem.

Although it is often said that the bulk of the arid lands are unfit for crop production, farmers would continue to grow crops during the foreseable future. To put the economy of the arid areas on a sound footing, it becomes necessary to develop an appropriate crop-production technology dovetailed with the variation in agro-meteorological conditions. Scientific crop production based on the principles of conservation and organic recycling, apart from enhancing the productivity of the arid-zone ecosystem, can also check desertification appreciably in the long run. All the research and development efforts should be directed towards this achievement of this objective.

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PLANTS IN RELATION TO SOIL-MOISTURE CONDITIONS OF THE ARID AREAS

A. N. LAHIRI

THE compelling needs of desert reclamation and the global efforts to arrest desertification are, in fact, directed largely towards resolving an apparent contradiction of essentiality of water for plant life and its general shortage in the arid areas. The low and erratic rainfall being the most serious constraint among all other factors which run counter to the establishment, growth and yield of plants in desert areas, the gathering of information on plant responses to soil-water conditions assumes a great practical significance. The crux of the problem is to determine the variabilities of soil-water conditions and the water balance of the soil profile invaded by the roots, the availability of moisture and its use over time and the responses of plants under the given conditions of the soil-environment. The purpose of this paper is to examine briefly some of the above-mentioned aspect, with special reference to the plants of the desert of western Rajasthan.

VARIABILITIES OF SOIL-WATER CONDITIONS

Influence of rainfall. A study (Lahiri, 1975b) of the soil-water conditions in the active root-zone of a pearl-millet field over several years at Jodhpur suggested two major conditions of soil drought. In one case, low soil-water conditions prevail owing to the low precipitation throughout the growing period of the crop, and in another, the erratic distribution of precipitation subjects the plants to sporadic droughts. The former condition leads to the extremely poor growth and yield of the plants and in the latter case, the dry matter production and yield of the crop may fluctuate from one year to another, depending on the stage of growth at which the drought was experienced. Besides, variabilities in the intensity and distribution of rainfall may often cause wide deviations in soil-moisture conditions from one area to another in the same season.

Influence of topography, landform and soil. Variations in soil-moisture conditions brought about by the topographical and landform variations have a significant bearing on the land use and plant production in the arid areas. Although there is a general appreciation of rainfall variations due to topography, soil-moisture variations because of slope, soil depth, and soil character, there still remains ample scope for the quantification of the moisture regime of different soil-geomorphic units of the desert. The importance of this aspect is easily realized if we consider that variations in the depth of soil alone may often influence the moisture availability and plant growth. It has often been observed in certain regions that the inter-dunal areas may have higher soil moisture than the top of the dune. A contrasting picture of the soil-moisture condition again emerges when the moisture status of the stabilized (with vegetation) and bare (without vegetation) dunes of this area are compared (Lahiri, 1964; Krishnan *et al.*, 1966). The data presented in Table 1 indicate that a substantial build-up of moisture is possible in the bare dunes, pre-

Table 1. Soil-moisture status of stabilized and unstabilized dunes near Bikaner

Depth (cm)	October 1973 % moisture		January 1974 % moisture		April 1974 % moisture	
	Stabilized	Unstabilized	Stabilized	Unstabilized	Stabilized	Unstabilized
0–15	0·2	0·8	0 1	1·0	0·3	1·1
15–30	0 4	2 8	0·2	3·1	0 5	3·4
30–45	0 6	4·6	0·5	5 0	0·7	3 8
45–60	0·5	5 0	0 6	5·5	0·6	4·9
60–75	1 0	5·5	0 4	5·9	0 8	5 6
75–90	0·8	5·8	0 7	6 0	0·5	5·8
Moisture content in mm	7·87	55·12	5·63	59·61	7 65	55·36

sumably because of the absence of transpirational losses from plants, as encountered in the stabilized dunes and the mulching action of the sand on the surface. The available reports (Mann *et al.*, 1976) indicate that this conserved moisture supplemented with the prevailing rainfall is adequate for the cultivation of water-melon and long-melon on the bare dunes of the Indian desert.

The frequent occurrences of carbonate pan or *kankar* pan (known as 'rotha' in common parlance) in the soil profile also has an important bearing on the soil-moisture status and vegetation. Roy *et al.* (1969) from their investigations in Jodhpur, Barmer, Jalore and Pali districts indicated that these pans had developed owing to the catamorphic processes in the weathered zone of the regional geological formation (i.e. granite and volcanics), and when this pan is one to one metre and a half in thickness, it is impervious. Such a pan may be found exposed to the surface or may lie at various depths up to 100 cm or more. Plant growth is impeded owing to the limitations of moisture and root growth in the shallow soils over such calcareous pans. Kaul and Ganguli (1964) reported that the success of plantations of forest-trees could be achieved in such areas (soil depth, 22.5 cm; rainfall, 375 mm) only by deep soil working in the pits.

Apart from above factors, variations in soil conditions, as such, have a significant bearing on the problem. Although sandy soils generally predominate over vast stretches of western Rajasthan, reports of the Basic Resources Survey of this Instiutte indicate a considerable deversity of soil conditions. In the Jodhpur District (area about 22,640 km^2) alone, seventeen soil series have been indentified on the basis of soil texture (R.P. Dhir, personal communication). The observation has an obvious significance on the regional soil-water condition and land use. For instance, the average water-holding capacity of the sandy to loamy-sand soils of the Chirai series was about 27%, that of the loamy soil of Gajasinghpura series it was about 42%, whereas in the heavy-textured soil (clay loam) of Asop series, it was about 54%. These variations, apart from other diversities of the desert, suggest the need for the standardization of separate strategies for production optimization in the different regions. The presence of silt and clay particularly needs a special reckoning in this respect. Kolarkar and Singh (1971) from their analyses of two hundred soil samples from various parts of Rajasthan indicated a significant relationship among silt, clay, silt+clay and the moisture constants, such as the moisture equivalent and the water-holding capacity. Silt was found to have the maximum influence on both these moisture constants, clay being the next and silt+clay the last. This finding is very meaningful owing to the general preponderance of sand in the soils of western Rajasthan. The amount of organic matter generally being low (0.03 to 0.45 per cent organic carbon), it may not have any special relevance to moisture retention in the soil. It has been found (Aggarwal and Lahiri, 1976) that the growing of vegetation on the bare dunes of Bikaner (average rainfall, 291.3 mm) and the associated silvi-pastoral management for over 18 years has brought about only a slight increase in the organic carbon of the surface soils. The percentage of organic carbon of the surface soils of the stabilized dunes varied from 0.08 to 0.12, against 0.02 to 0.04 found in the adjacent unstabilized dunes.

The rocky areas in this respect pose a unique problem. In such habitat, grasses, e.g. *Eleusine compressa* and *Aristida adscencionis* and trees, e.g. *Acacia senegal* and *Anogeissus pendula,* are often found. It is presumed that roots follow physical weathering and the acidic root exudates help often to disintegrate the rocks. It is possible that a process of water absorption by the rocks during the rainy season and its release to the invading roots in summer may also be operating in the rocky areas.

Rain interception by vegetation and its influence on soil moisture. Long-term studies elsewhere have shown (Baver, 1956; Rutter, 1958) that 10 to 55 per cent of the rainfall may reach the soil, depending on the degree of vegetation cover and the type of plants. The proportion is obviously influenced as much by the size, frequency and duration of the component showers as by the differences in the structure of the cover. There are also other considerations of foliage characteristics, their wetting properties, absorption by dead plant parts, stem flow, etc. Although such information is rather scarce in respect of western Rajasthan, yet it has an important bearing on the agri-silva and silvi-pastoral programme in all arid areas. Studies undertaken by Gupta *et al.* (1975) under Jodhpur conditions indicated that the soil moisture in the 90-cm profile of the *Eucalyptus* forest increased from about 4 cm to 7.5 cm after a 38.1 mm shower during September 1969, but the order of increase was much less in the fallow land, grassland and in the *Acacia* forest. A comparative study on the soil-moisture status in the 120-cm soil profile of different tree communities undertaken here by J.P. Gupta (personal communication) indicated that the moisture regime remained generally higher under *Prosopis cineraria* and *Tecomella undulata* than under certain other species, e.g. *P. juliflora, Albizzia lebbek* and *Acacia senegal.* This could be one of the reasons of the increased growth of the ground cover, often observed beneath the trees of *P. cineraria.* Shankar *et al.* (1976) obtained a yield of 2 3 t/ha of dry herbage from under *P. cineraria* against 1.66, 1.32, 0.85, and 0.78 t/ha from under *T. undulata, A. lebbek, P. juliflora* and *A. senegal* respectively. Since this tree (i.e. *P. cineraria*) has a capacity to absorb moisture from sporadic rains through its foliage (Bhatt and Lahiri, 1964), the enrichment of soil moisture may be possible only under conditions of heavy showers.

SOIL TEMPERATURE IN THE CONTEXT OF SOIL MOISTURE

A number of studies (Shankarnarayan *et al.*, 1965; Abichandani *et al.*, 1967; Krishnan *et al.*, 1966; Mann *et al.*, 1976) have been undertaken on the temperature profile of the soils of western Rajasthan. The findings generally indicate that during summer, high surface soil temperature declines fast with the depth and levels off at lower depths. The diurnal temperature changes at the lower depths are smaller than those on the surface of the soil. During winter, the lower soil layers are warmer than the top. Abichandani *et al.* (*loc. cit.*) observed that the cooling of the layers of the surface soil during the night and in the early hours of the morning resulted in a marked drop in vapour pressure, with a consequent movement of water vapour from the warm moist zone below. This was followed by warming up during the day and this warming up caused the evaporation of surface stored water with censequent lowering of evaporation front. During summer, the temperatures of the surface layers were higher than those at the lower depths. This observation suggested a possibility of the vapour-phase transfer of moisture to lower depths.

These observations further indicate that relatively low temperature conditions of the lower soil layers, particularly during the hot summers, permit the root-systems to avoid hyperthermic conditions. Again, it appears that wide temperature differences in the profile obviously bring about a vapour-phase movement of the moisture which has a far-reaching influence on the overall soil water balance. Recent evidences suggest that in the desert soil with a strong daily temperature wave, the vapour flux in the soil may be of a magnitude comparable with the liquid flux.

WATER USE BY DESERT VEGETATION

Since the soil moisture conditions have a direct influence on the utilization of moisture by plants, the quantification of water use by the desert vegetation assumes a singular importance. The close relationship of water use with plant production, on the one hand and the hydrological cycle on the other, makes it again an important area of study, more so, in the arid and semi-arid areas, where rainfall is meagre and evaporation is large.

Water loss from desert trees. Specific studies (Lahiri, 1975a) on the water-use behaviour of the vegetation components of the Indian desert have indicated that most desert trees display a large water turnover which is possibly due to their capacity to tap water from great depths. A community of *Prosopis cineraria,* consisting of 50 trees may lose as much as approximately 222 mm of moisture annually from a hectare of land. Changes in the moisture conditions in the upper soil layers hardly influence the transpiration and relative turgidity of the established trees, as is discernible in the case of their seedlings with a limited root-system. Certain plants, e.g. those of *Tecomella undulata,* have the capacity to reduce the total water output by reducing their transpiring surface (either by reducing their leaf growth or by shedding their leaves) under adverse soil-moisture conditions, although the rate of transpiration per unit of the leaf area may often remain undiminished.

The water-use by grasses. Owing to the shallow root-system, the growth of rain-fed crops and grasses is largely restricted to the rainy season, which extends from about the middle of July to September. The use of the hydrological equation for the water balance of field plots has helped to ascertain the consumptive use of moisture of such plants. In a study undertaken during 1963, it was observed that 162.9 mm of water was utilized by the ground cover of *Dactyloctenium sindicum, Cenchrus setigerus, Eleusine compressa, Crotalaria burhia, Aristida funiculata, Cenchrus biflorus, Cyperus rotundus, Gisekia phanaceoides, Brachiaria ramosa,* etc., when the rainfall during the growing period (July-September) was 163.8 mm. The soil moisture in the profile up to a depth of 2 metres beyond September was below the permanent wilting percentage and it was obvious that the ground cover of vegetation completely utilized the available moisture in the upper layer of the soil. Moisture seems to be the main limiting factor in the formation of the ground cover of vegetation, as supplemental irrigation during the dry period led to the rejuvenation of growth and to an increase in net assimilation and the leaf area.

Studies undertaken during the favourable-rainfall year of 1976 (total rainfall, 639.7 mm; rainfall during July to November, 334.3 mm indicated that in a pure stand of *Cenchrus ciliaris* (Str. No. 358), the consumptive use of moisture increased from 152.2 mm at 10-day intervals of cutting (cutting at 5-cm height) to 162.2 mm at 60-day intervals of cutting. Similarly, in *Lasiurus sindicus* (Str. No. 319), 168.8 mm of water use at 10-day intervals of cutting increased to 185.8 mm at 60-day cutting intervals. It was found that the fodder yields increased significantly at longer intervals of cutting, associated with an increase of water-use efficiency. Such informations on specific soil-rainfall conditions should provide useful guidelines for range management in the arid and semi-arid areas.

The water-use by crop plants. The quantification of water-use behaviour of the principal crops of this area has been largely achieved by using the hydrological equation for water balance in field plots.

The weekly assessment of the consumptive use of moisture of different varieties of legumes, e.g. *Cyamopsis tetragonoloba*, *Phaseolus aconitifolius* and *P. aureus*, over two consecutive cropping seasons of 1964 and 1965 suggested that the moisture loss increased with the age of the plant and declined again at maturity. It has often been observed that the consumptive use in certain weeks may (not having rains) be low, or may even become negative. This observation suggested the possibility of a recharge of moisture which was about the same as, or slightly more than, the actual consumptive use. Again, the sum of the consumptive use and other losses of moisture for the whole growing period may often be found to be higher than the actual precipitation. Since an upward movement of water due to capillarity is low in these sandy soils, the lateral movement of moisture or a vapour-phase movement through temperature gradient, as discussed earlier, may be a possible cause of this phenomenon.

This study on the legume varieties again indicates that the water use, on the one hand, may vary owing to the species and varietal differences, and due to the rainfall conditions, on the other. Further information in this respect was gained from the water balance of field plots under different varieties of pearl-millet (Table 2). It may be observed that the water use by different varieties of pearl-millet changed widely in different years, depending on the prevailing rain-fall conditions. Low rainfall decreased the water use owing to the decrease in vegetative growth and conversely it increased under high-rainfall and favourable soil-moisture conditions, which led to an increase in growth. Similarly, deep drainage increased from zero (as during 1968 and 1969) to a high value (as in 1970) because of the variation in rainfall conditions. However, the proportion of rainfall which will be used by the plant component and that which will go down as deep drainage seems to depend largely on the distribution of rains. For instance, precipitation was more during 1970 than that during 1971, but the utilization of moisture by most of the varieties was more during 1971, whereas deep drainage was more during 1970. The distribution pattern of rainfall during these two years (Table 3) shows that an even distribution of rains during 1971 helped the plants to utilize more moisture but during 1970, higher rainfall in the major spells (as in August and September) enhanced deep drainage.

Table 2. The consumptive use of moisture and the losses due to deep drainage in different years from fields under different varieties of pearl millet. N and P_2O_5 each @ 20 kg/ha were applied in all cases

Year	Variety	Total precipitation (mm)	Consumptive use of moisture (mm)	Deep drainage (mm)
1966	RSK	263·3	180·0	54·5
	RSJ		176 8	30·5
	Ghana		183 5	20 9
	RSK		131 8	Nil
	RSJ		120·0	-do-
1968	Ghana	178·6	130·3	-do-
	HB 1		158·8	-do-
	HB 2		133 4	-do-
	RSK		68·3	Nil
	RSJ		79 7	-do-
1969	Ghana	92·7	73·1	-do-
	Chaddi		63 2	-do-
	HB 1		86·3	-do-
	RSK		155·8	297·7
	RSJ		130·8	306 6
1970	Ghana	594 8	152·5	326·4
	Chaddi		154·1	353·9
	HB 1		171·1	290·3
	RSK		214·4	38 2
	RSJ		183·7	77·7
1971	Ghana	307 6	108·7	37·7
	Chaddi		204·0	49 6
	HB 1		187 7	55 5

PLANT RESPONSES TO SOIL-MOISTURE CONDITIONS

Considerable effort has been diverted towards the understanding of the influences of soil-moisture conditions on the germination, growth and yield of plants of this area as also on their effects on metabolism.

Germination in relation to soil moisture. Apart from low rainfall, the quick depletion of moisture from the surface soils poses a serious threat to good germination and plant establishment. In order to

Table 3. Distribution of rains in mm during 1970 and 1971 at Jodhpur

	Rainfall in mm in different months												
Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1970	—	8 3	1 2	—	26 3	44 0	59 4	364 2	91 4	—	—	—	594·8
1971	—	2·9	—	2·5	25 9	57·4	79·8	103 6	32 7	2 9	—	—	307 6

evade these difficulties, certain plants, e.g. *Aerva tomentosa*, *Dichrostachys glomerata*, *Elusine compressa*, *Dactyloctenium sindicum*, and *Sporobolus* sp., display adaptations of vegetative propagation by producing runners, stolens, etc.

However, specific studies (Lahiri and Kharabanda, 1963a) on the moisture requirements for the germination of prominent fodder grasses, such as *Lasiurus sindicus*, *Cenchrus ciliaris* and *Cenchrus setigerus*, have indicated differences in the need for moisture for germination and in the rates of water uptake of their seeds. The glumes which enclose the seeds of these species also display marked differences in their hygroscopic properties. Although the capacity of quick water uptake by the seeds has generally been found to be an essential trait for successful propagation under desert conditions, the occurrence of germination inhibitors in the propagative bodies of the above-mentioned grasses (Lahiri and Kharabanda, 1963b) and also in the leaf litter of certain tree species, such as *Prosopis juliflora* (Lahiri and Gaur, 1969), emphasizes the indirect need of water for leaching these water-soluble inhibitors either from the propagative bodies for the germination of the enclosed seeds or for leaching them from the leaf litter and the soil, as in the latter case, to enable other species to grow within the tree community.

Studies on the germination of the tree species, e.g. *Prosopis cineraria*, *P. juliflora* and *Albizzia lebbek*, have indicated that unfavourable soil-moisture and temperature conditions (optimum temperature around 40°C) prolong the germinative period. Although their germination under the optimum conditions of the laboratory was high (ca. 70-80 per cent), yet their emergence under rainfed field conditions dropped to hardly 30 to 40 per cent. However, diverse uncertainties, such as long germinative period, the burial of seeds under sand, the destruction of seeds by rodents and other pests preclude the prospects of successful tree establishment by direct sowing in the desert. The transplantation of nursery seedlings in this connection is favoured more than direct seeding.

Influences of soil-water deficit on plant performance : The influence of soil-water deficit at different stages of development of pearl-millet have been investigated by Lahiri and Kharabanda (1965) and Lahiri and Kumar (1966), with special references to the alterations of different indices of plant performance. It was observed that, in general, susceptibility to drought increases with age of plant, although the magnitude of responses altered in different phases with respect to different characters under consideration. It was further observed that water stress at the onset of the reproductive phase has the maximum adverse effect on the yield. The reversion of drought effect in the young plants and the weakening of this reversion mechanism with age suggested a close relationship of drought sensitivity and senescence in the case of pearl-millet. An increase in grain yields due to early drought has been observed in this crop, as reported earlier in the case of wheat (Chinoy, as quoted by Asana, 1960). However, when the period of this drought is long and the intensity is high, a large mortality of seedlings inevitably decreases the yield.

Rainfed crops, e.g. pearl-millet, are usually subject to higher soil-water stress at the advanced stages of flowering and ripening. Supplemental irrigation, wherever possible, at the critical stage of the onset of ear emergence seems, therefore, to be an easy way of stabilising yield. Similarly, the adverse effects or early drought on pearl-millet may be avoided, if the seedlings are raised in irrigated micro-plots, and transplanted during adequate rains. Although this crop is normally sown in early July with the break of the monsoon, transplantation may be done up to the middle of August without any adverse effects on yield. In one study conducted during 1971, transplanted pearl-millet (var. HB 4) gave a yield of 26 q/ha, with 80 kg/ha each of N and P_2O_5.

Effects of moisture stress on nitrogen metabolism and nitrogen uptake : Studies on the nitrogen metabolism (Lahiri and Singh, 1968) indicated that in the initial stages of tissue dehydration, protein synthesis was impeded and proteolysis was triggered off at wilting. During the drought cycle, there was an indication of an increase in nitrogen concentration in the tissue. Ammoniacal nitrogen which could be detected in the wilted plants showed a sharp decrease on rewatering, with an associated increase in the level of amide nitrogen, suggesting a quick incorporation of ammonia into organic acids as a measure against ammonia toxicity. Studies on the effects of hyperthermia on nitrogen metabolism (Lahiri and Singh, 1969) indicated that, unlike moisture stress, high temperature directly caused a breakdown of proteins. Investigations on the influences of soil moisture on the nitrogen metabolism further indicated that rewatering after a period of drought enhanced the synthesis of proteins and, consequently, the protein concentration after the termination of a drought cycle was more than the initial concentration.

The alterations of plant growth and metabolism under different regimes of soil moisture are very relevant in the present context, as in nature there is a continuous drift of soil-moisture tension. Studies (Lahiri and Singh, 1970) undertaken on different varieties of pearl-millet indicate that under critical conditions, when the soil moisture fluctuated between ca. 1/3 and 15 atm. tension, the yield was depressed equally in all the varieties. The results generally suggested that varietal traits were discernible when the soil-moisture condition was not too critical, although the performance, as such, in all cases was adversly affected under higher-tension regimes (i.e.ca. 1/3 to 1 atm. and 1/3 to 8 atm.) than in control (ca. 1/3 atm.). The choice of improved varieties, therefore, has a singular importance in the drought-prone areas.

It has further been observed that the vegetative growth, as such may be reduced under adverse soil-moisture tension, but the concentrations of both total nitrogen and protein nitrogen increase in the tissue, irrespective of the age of the plant. A reduction in dry matter may lead to a higher total N concentration, whereas the higher protein synthesis during the 'wet' phase after the dry spell may account for the higher protein N concentration in the tissue. Unfavourable soil-water conditions also increase the N concentration of the grains of pearl-millet, although the yield was decreased. It has been speculated that the flow of nitrogen in the grains was less subjected to unfavourable moisture conditions than the flow of carbohydrates. It is, therefore, a natural redemption that despite the low productivity from arid areas,the quality of the produce is generally superior to that obtained from areas having favourable soil-moisture conditions.

PRINCIPLES OF PRODUCTION STABILIZATION UNDER LOW SOIL-MOISTURE CONDITIONS

Drought-causing sustained low-moisture regime. Drought caused by low precipitation in some years as described earlier, may be encountered very frequently in this area, and the production stabilization under these conditions becomes extremely difficult. It has been found that under such conditions, effects due to fertilizers and those due to varieties do not become significant. These effects in a good-rainfall year display a high order of statistical significance. Investigations (Lahiri, 1975b) directed towards the stabilization of production in such low-rainfall years have indicated that when rainfall is delayed and is expected to be low, it may be advantageous to grow certain legumes, e.g. *Cyamopsis tetragonoloba* (*guar*) and *Phaseolus aconitifolius* (*moth*), which use less water than pearl-millet, which has a relatively high water need.

C-4 plants of western Rajasthan in relation to the efficiency of water use. During the recent years (Huber *et al.*, 1973; Sankhla *et al.*, 1975), a large number of species (including grasses) of the Indian desert have been found to have C-4-dicarboxylic acid pathway for photosynthesis. However, while discussing the water-use behaviour of grasses, it has been mentioned earlier that the consumptive use of moisture of *C.ciliaris*, *L sindicus*, which are C_4 plants, may be substantial, when there is no constraint of soil moisture. Again, it has been found that the water-use efficiency in the context of dry-matter production may also vary widely among the C_4 plants. For instance, the water-use efficiency of *C. ciliaris*, *C. setigerus*, and *L.sindicus* grown under indentical conditions was in the order of 21.8, 8.4, and 19.1, respectively. These observations indicated that wide variations in productivity ranges might be encountered among the C_4 plants of this area. It is, thus, necessary to ascertain the productivity ranges in the context of soil-moisture and management conditions, even if the plant is generally considered well adapted to arid conditions.

INSULATION MEASURES UNDER SPORADIC DROUGHT

The irregular distribution of precipitation often creates another condition of drought where the plants may be subjected to moisture stress at any stage of growth. Such sporadic droughts may be encountered both in high and low-rainfall areas. On the basis of a large number of experimental data, it has been concluded (Lahiri, 1975b) that the adverse effects of droughts, no matter at which stage of growth the water shortage is experienced, could be substantially evaded where optimum plant vigour was induced by adequate soil fertility. This concept of nutrition-induced vigour as a means of drought avoidance has further gained support from studies (Kathju and Lahiri, 1976), which indicated that plants raised under optimum soil fertility displayed higher activity of enzymes and showed a higher chlorophyll content of leaves under desiccation than plants raised under low soil fertility. It has been found that the tissue turgor is unlikely to be the key to general growth reduction under water shortage. It has been speculated that growth and metabolic efficiency is more dependent on nutrition rather than on tissue hydration atleast up to a certain level of water shortage. The flow diagram under Fig.1 explains the overall mechanism of actions that has been derived from various experiments.

The foregoing concept holds considerable promise for arresting desertification of the semi-arid and high-rainfall areas located at the fringes of the desert.

Prospects for the reduction of irrigation need. The increasing emphasis on irrigation in the Indian arid zone necessitates the standardization of irrigation norms in the context of the regional environment. Water being the most precious input, attempts were made to apply the foregoing concept of nutrition-induced vigour for the stabilization of wheat yield under a low level of irrigation. It was found (Lahiri, *loc.cit.*) that a substantial production of wheat (var. RS 31-1) could be achieved with less water by optimizing the inputs, e.g. nitrogen and phosphorus. A yield of about 20.8 q/ha under 80 kg/ha each of N and P_2O_5 was achieved when the plants received only 24.5 cm of water. However, plants without any nitrogen and phosphorus, in the loamy-sand soil of Jodhpur gave a yield of only 6 5 q/ha with 39.5 cm of irrigation water. Experiments under both open and pot-culture

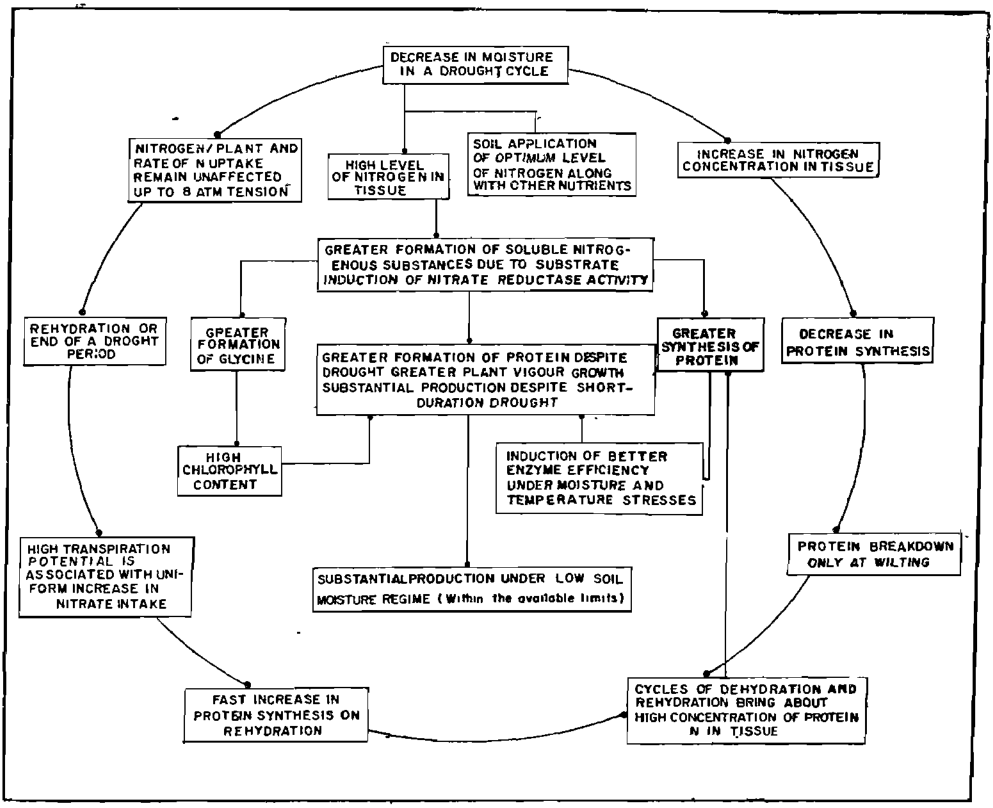

Fig. 1. The mechanism of actions envisaged for the nutrition-induced vigour as a measure for avoiding the adverse effects of sporadic droughts

conditions suggested that different levels of production could be achieved at the same level of water use, under irrigated conditions, by a progressive optimization of inputs. Ram and Lahiri (1974) from the economic analyses of wheat production under 'high' (ca. 1/3 to 1 atm. tension) and 'low' (ca. 6 to 15 atm. tension) moisture availability (with adequate fertilizers) indicated that the returns over fertilizer cost would be Rs 2,668.80 under high and Rs 861.29 under low-moisture availability (the selling price of wheat was assumed to be Rs 90 per quintal).

The foregoing results indicate that a farmer in this area, having a well of limited discharge, may expect a reasonable yield by spreading the limited water resource over a larger area. Singh (1976) in this contest emphasized the point that a lower average yield over a larger area could bring about a higher total benefit in the arid areas than from the most profitable yields from a small area.

An understanding of the basic principle governing the process of nutrient use under low soil water condition was possible when our results indicated that within the available limits of soil moisture increase in the level of soil nutrients, increased the absolute quantities of these nutrients in the plant with an associated improvement of the performance, irrespective of the tension. The magnitude of this increase was, however, less at high tension ranges. The trend of result has been illustrated in the Fig. 2 with special reference to the root growth and the

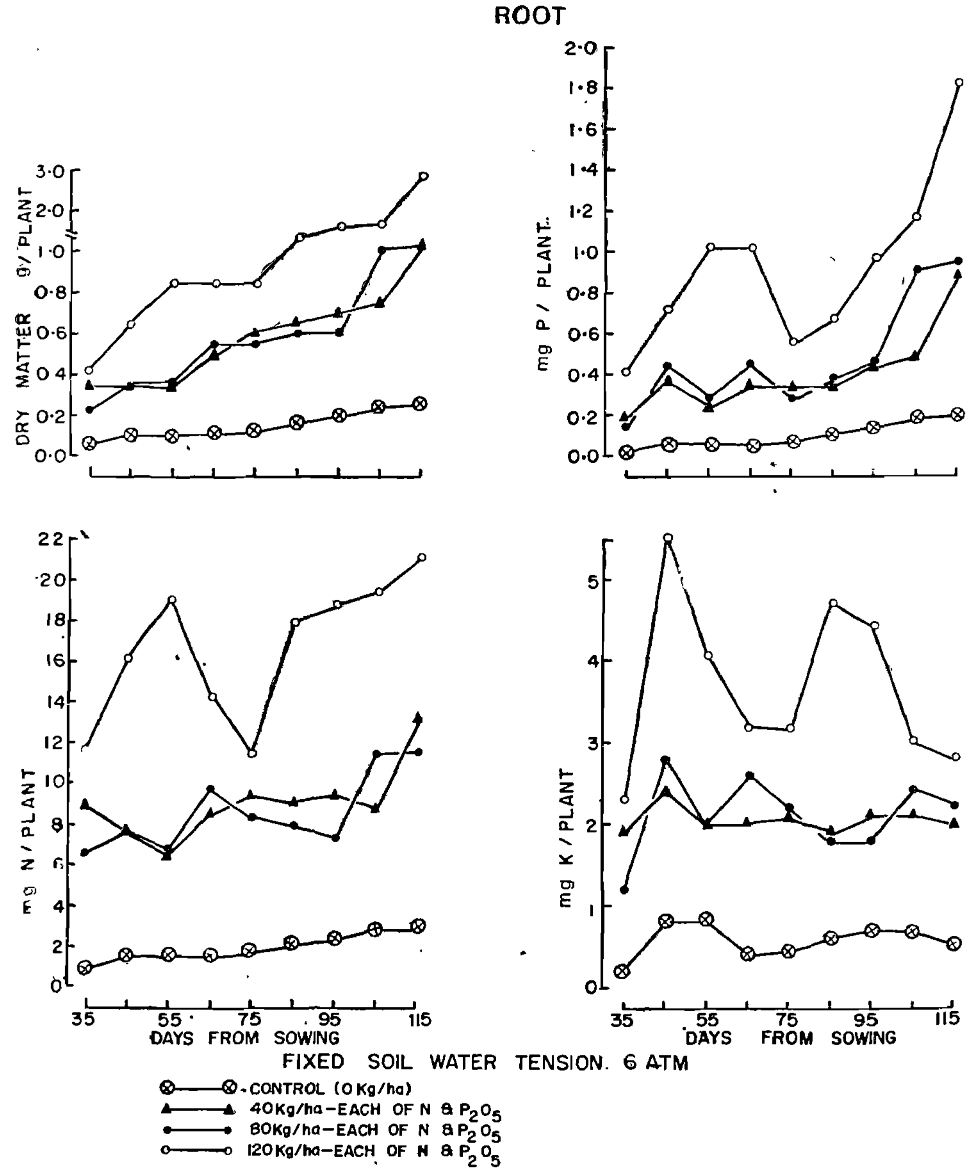

Fig. 2. Root growth and absolute quantities of nitrogen, phosphorus and potassium in the root of wheat raised under different soil fertility conditions and at water tension of ca. 6 atm.

nitrogen, phosphorus and potassium contents of the roots of wheat plants, grown at ca. 6 atm. tension and under different soil fertility conditions.

Innovations related to improvement of soil water conditions. Various technologies have also been evolved over time for the improvement of soil water conditions and plant production in the dry regions (National Academy of Sciences, Washington 1974). In arid areas of Rajasthan, promising results have been obtained by land shaping and use of runoff water in agriculture (Singh *et al.*, 1973; Singh, 1976), water harvesting from natural catchments (Prajapati *et al.*, 1973), bunding in sandy-loam soils (Misra, 1966), contour bunding and furrowing (Ullah *et al.*, 1972), use of subsurface barriers, breeding of sandy soils with pond silt (Gupta, personal communication) and also by subsurface incorporation of the plant parts of a latex containing plant like *Calotropis procera* (Singh, 1973).

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25

OPTIMUM UTILIZATION OF LIMITED WATER SUPPLY

S. D. SINGH

THE maximum yield is usually obtained by applying irrigation at the rate of potential evapotranspiration (ET). In the fulfilment of this expectation, water is used wastefully because of the inverse relationships between evaporative losses and the extent of crop cover until it is 50% complete, and between irrigation efficiency (the percentage of irrigation used in ET) and the non-ET water uses (deep percolation and unutilized moisture at maturity) under conditions of potential ET rate. From these observations, a few things can be inferred. First, for crops which do not have complete cover at all times, the amount of ET required for maximum yield would be less. Second, the opportunity for the rational use of limited water lies in methods that vary the relative proportion of the nongrowth-related evaporation to the growth-related transpiration and eliminate the non-ET water uses. Third, the continuing adherence to the "traditional approach" to the problem of improving water-use efficiency best suited to the area of water abundance, limited land is no more justified in water-deficient regions. Time has come for a switch-over from "this" to the "optimization" approach which attempts to minimise the seasonal ET *per unit area* or *per unit yield* with the least accompanying loss in harvestable yield.

Interwoven is the need for a shift from individual crop water-management approach to water management of the "farm unit" as a whole in all matters of limited water allocations. Emphasis in this chapter will be placed only on that part of these aspects which are either manageable or have notable policy implications in the water-project planning rather than in the reporting of voluminous literature relating to these subjects.

The ET is the field-level water parameter, derived from the rainfall, irrigation, and the available soil water at planting. Obviously, a wholesome emphasis would be on the management aspects of water after it has reached the field through one or all of the three ET sources. Particular reference will be made to arid and semi-arid regions of Rajasthan. But the basic principles and approaches developed to achieve the optimum use of limited water may serve as a guide to other arid and semi-arid regions of the world.

MECHANISMS THAT VARY THE RELATIVE PROPORTION OF EVAPORATION TO TRANSPIRATION

In field agriculture where the basic water parameter ET includes surface evaporation, any amount of technology, no matter how efficient, can eliminate evaporation from the soil. Nevertheless, the mechanisms capable of restricting the availability of water to the evaporative site, reducing the availability of energy to the soil, and limiting heat or vapour exchange between the soil and the atmosphere can minimize it, making water available more for transpiration which is most directly related to yield. Therefore, the best opportunity for saving water lies in methods influencing these factors of evaporation and the relative proportion of evaporation to transpiration. Some of these factors are: the elimination of weeds, the use of mulches, the application of the optimum leaf-area concept, and irrigation in terms of ground cover.

A. Mulches related to moisture conservation

The effectiveness of mulches for moisture conservation has varied, depending upon the soil, the climate, the crop, the type of material used, and the degree of cover on the soil. There is no controversy as a result with one's experiment, but with the interpretation and application of results. The objective here is not to resolve the controversy but to analyse how far mulches would be helpful or not helpful in moisture conservation under specific soil-climate situations of this region. Therefore how the evaporation proceeds and what processes inside the soil contribute to it should be sufficiently known so that necessary manipulation in the use of mulches can be done to reduce the evaporative loss to its minimum. It is in the context that some elementary facts are briefly mentioned here.

For a day or two after wetting, the water is freely available, evaporation proceeds at a rate in direct proportion to the energy available, but slows down as the soil dries at a rate proportional to the water content and universally proportional to time. The drying front advances into the soil profile linearly with time, but the evaporative site seldom exceeds 5 cm below the soil or is generally at or near the surface. Thus we see that the water content and hydraulic conductivity are interacting to characterize the water diffusivity and their contributions are texturally controlled.

In coarse-textured soils, the surface 10-cm layer is single-grained, dry aggregates of size>2 mm are hardly 1 %, capillarity is almost nil, pore discontinuities are predominant, and hydraulic conductivity is high at low, and is low at high suction. Added water thus moves down at a rapid rate and is placed deep in the profile safe from evaporation. Its upward flow is very slow because of pore discontinuities. As a result, the evaporative site dries up quickly, the thermal contact coefficient is reduced, the liquid flow of water ceases, the evaporative cooling of the soil surface becomes nil, and much of the energy is transmitted to the soil until ground cover becomes incomplete and is consumed in heating the air which, in turn, heats up the immediate soil surface. Nevertheless, the evaporative losses will be less. Because the dry layer retards vapour escape owing to pore discontinuities, and also because the dry air within and immediately below the evaporative site is an effective thermal insulator. Under these conditions, it is doubtful that the net effect of organic mulches, and the ineffective barrier to vapour escape may be of any utility. Frequent reference to mulching will also be made in the context of the asphalt moisture barrier.

B. Optimum leaf-area concept related to better use of water

Here we limit our discussion to the leaf-area concept synonymous with crop cover, as related to the relative proportion of evaporation to transpiration. As seen from Fig. 1, the leaf-area index (LAI) of annual crops, e.g. wheat, starts from zero early in the season, increases rapidly to a maximum, remains at the maximum level for a short period, and then declines rapidly. Hence to maintain the "optimum" leaf area at all times is difficult. However, the system which comes closest to this ideal will be the most efficient.

Early in the season when ground cover is least, ET is also least. A large part of water use is in the form of evaporation and is least through transpiration (Table 1).

To ensure that the radiant energy is used in transpiration much more than evaporation early in the season, it is desirable to have an optimum density of vegetative cover by properly adjusting the row-spacing and seed-rate, by selecting the most favourable time of planting, and by a fast development of crop canopy through adequate fertilization early in the season.

Table 1. Relative amounts (inches) of transpiration T by the maize crop and evaporation E from the soil in Ohio (Harrold *et al.*, 1959)

Period	T	E
May 1—June 5	0	3·69
June 6—June 30	1·77	2·47
July 1—July 31	4·14	2·53
August 1—August 31	2·40	1·59
September 1—September 9	0·16	0·38
Season: March 1—September	98·47	10·66

Or transplant seedlings, where the nature of the crop and the labour needed do not place added constraints on the economics of the practice.

As the percentage crop cover increased up to 50% through an increase in the leaf-area index from 0.3 to at about 1.2, ET increased, more through an increase in transpiration and less through evaporation (Table 1), during weeks 7 to 12, the LAI is more than 3, or the ground cover is>50% complete. But beyond a certain point (LAI = 3.5 in this case), the ground cover did not increase because of the mutual shading of leaves to a large extent. The crop will have attained its maximum aerodynamic roughness. Any expanse of canopy thereafter through management manipulations will have no important effect on transpiration, because the increased interception of energy will be compensated for by a decreased effect of turbulent transfer. During this period of crop cover>50% complete, the ET crop exceeded the evaporation (Fig.1), and the evaporation from the soil contributed only a small portion of the total ET. Cultural practices, e.g. weeding and mulching, which effect only the direct evaporation from the soil will have but a small effect thereafter on the total ET. The elimination of weed canopy early in the season, therefore, is one of the important practices to reduce the water per unit yield and the yield of commodity needed from a smaller total available water-supply.

The evaporation contributed a substantial part of water-use again when the crop approached maturity, the leaf-area index declined fast (Fig. 1), as the canopy allowed a substantial transmission of radiant energy to the soil. During this time, the ET continued, but at a diminish-

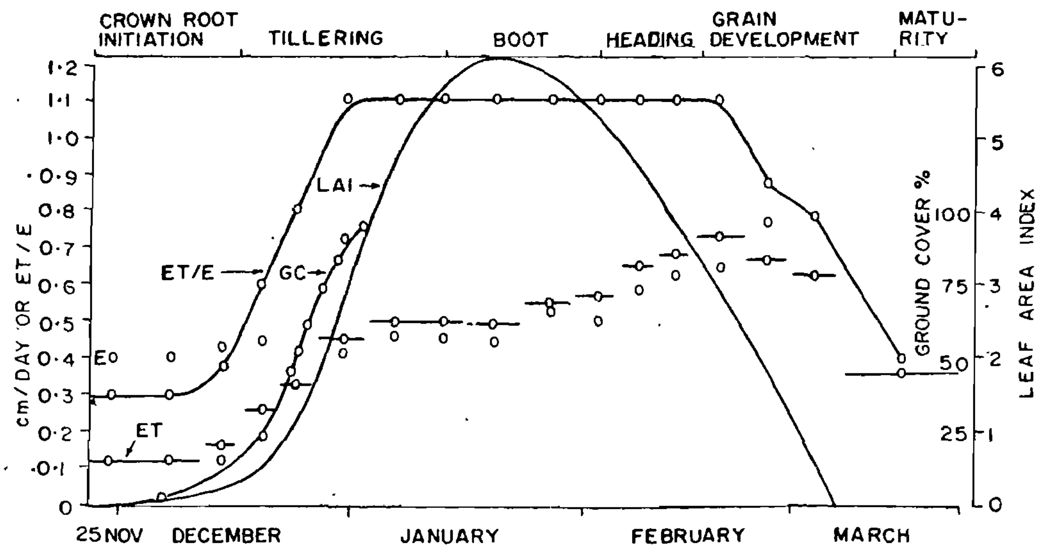

Fig. 1. Per cent ground cover (G.C.), ET, E (Evaporation) in class A pan and ET/E ratio in relation to seasonal changes with time in leaf area index (LAI)

ing rate. In most crops, it is for this reason that the soil moisture should not be maintained at a high level after maturation.

C. Irrigation in terms of ground cover

It may also be mentioned (though not shown in Fig. 1) that frequent irrigation until the ground cover is incomplete (LAI<1.2) will cause low ratios of transpiration to evaporation for 2-3 days subsequent to irrigation by excessive evaporation from the wet soil surface. Once the ground cover is complete (LAI = 1.2 to 3.5), the ratio is more than unity through the preponderance of transpiration, and evaporation, whatever value it may have, appears to become a constant percentage of ET. Efficient water management requires some restrictions on frequent irrigation early in the season until the maximum energy available is used through evaporation, on the one hand, and a prudent use of water is made during the period of complete ground cover, on the other.

On the basis of this observation the general recommendation (Misra *et al.*, 1969) after the first irrigation to dwarf wheat 21 days after sowing does not appear to be sound. More so, when the ET early in the season is less, and if the presowing irrigation has initially brought the soil profile to field capacity it can continue to meet the maximum or the near maximum ET demand easily for a month or so after sowing. The potential thus exists for saving an irrigation early in the season without impairing the prospects of a better yield. The works of Cheema and Malhotra (1975), Ram Niwas (1975), and Jaswant Singh (personal communication) are cited as evidences that suggest the application of the first irrigation in the case of dwarf wheat at the active tillering stage.

REMOVAL OF NON-ET WATER USES

The ET is derived from irrigation, the profile-water storage at the time of sowing and the growing season rainfall. Together, these sources constitute what may be termed field water-supply. Note that the irrigation is not all converted into ET. Whereas the available soil water in the root-zone at sowing time is converted into ET to the extent of 100 per cent, the conversion of rainfall into ET is generally close to 100% and irrigation include non-ET water uses. In this way, irrigation water=ET+non-ET, and irrigation efficiency is the ET expressed as the percentage of irrigation water purchased and applied. Therefore, water is greatest of concern to policy-makers, economists and engineers.

If this irrigation efficiency were 100%, the non-ET portion of water use would be eliminated and the relation between yield-field and water-supply would be similar to the linear yield-ET relationship. Unfortunately, the irrigation efficiency typically decreases as we approach the maximum ET (ET max) to attain the maximum yield (Y max). The reasons for these things are obvious. If irrigation is at some level well below that required for Y max, deep percolation losses can be made minimal or even eliminated. Additionally, all available soil water at sowing time will be extracted by the crop roots before maturity. When irrigation is sufficient to assure no ET deficit, some deep percolation is inevitable, and some available soil water will remain in storage at maturity. The non-ET water disposition also occurs when rainfall exceeds the size of soil storage, and the sandier the soil, the greater are the losses through deep percolation.

From the foregoing account it appears that the optimum water-use policy in arid and semi-arid regions should be to use subsurface barrier to apply the concept of modest irrigation, and to terminate irrigation at an appropriate stage to ensure that losses due to deep percolation are minimal, or even eliminated, and no available soil water remains in storage at maturity. The termination of irrigation will be discussed in the context of water-use optimization programme. The remaining two points are discussed here:

A. Subsurface Barriers for Moisture Conservation

To minimize deep percolation, the Japanese Desert Development Institute has introduced a technique for injecting a 3-mm-thick asphalt layer at a depth of 45 to 90 cm. In addition to making an effective use of the limited supply of irrigation water, the technique is claimed to prevent the salt in the desert sand from filtering up into the surface soil. In a recent study by J.P. Gupta (personal communication), deep percolation from asphalt-barriered profile was 4 out of 54 cm of rainfall. From the uniform profile, the loss was 22 cm. The additional low-tension water held in the root-zone boosted the yield of pearl-millet under rainfed conditions and of wheat under irrigated conditions. The claims of AMOCO (1971) regarding the ability of asphalt moisture barrier (AMoBar) to increase yields and improve farm profitability are further stimulating our interest, though at a price of $ 700 to 800/ha, which, they claim, the US farmers can afford.

Possible hazards of AMoBar

Though the results are of special significance, AMoBar is not for every farmer, for every crop, on all soils and under all conditions. It has particular promise in the case of money-spinning crops (vegetables, including groundnut and maize for cobs), in "sand" and some loamy sand, under natural-rainfall conditions. For irrigated conditions, the technique presumes that the water is of excellent quality in the requirement difficult to meet in this region where the problem of salinity in irrigation water is moderate to acute and wide-spread. The use of poor-quality irrigation water over and over again will accentuate the salinity level of the potential root-zone to such a degree that will render the cultivation of even tolerant crops most difficult. The handling of salinity will become difficult, especially when the leaching of salts cannot be integrated into the irrigation management of the stratified profile. Nor is there any scope for rain-induced leaching by fallowing during the following rainy season, in spite of the fact that AMoBar allows free water to seep down, but at a very low rate.

AMoBar confines the rain or irrigation water to a depth of 60 to 75 cm and the depth of its placement. The added water-supply and higher water diffusivity from shallow-perched water-table will result in considerably larger evaporative losses than from a uniform profile. Experimental data of H.P. Singh (personal communication) regarding the probable greater evaporative loss and less added yield from stratified profile than from a uniform profile are shown in Table 2. In 1974, a dry year, the added water-supply by run off concentration + barrier+organic mulch at 4 tonnes/ha brought 200 kg/ha extra yield of round gourd, over that from the runoff+barrier treatment. Under the flat-surface unstratified control, the water got the opportunity to move deep into the profile safe from evaporation, and that water the crop utilized and so was able to yield extra 410 kg/ha. During 1975, a normal year, regular rainfall in abundance overshadowed the ill effects of greater evaporation from the stratified profile and the yields for various treatments, as a result, did not differ significantly.

Table 2. Yields of round-gourd with and without bentonite moisture barrier during poor (—) and good-rainfall seasons

Treatments	Yield 1974 (dry)	Yield 1975 (wet)
Runoff+barrier	4,310 kg/ha	10,000 kg/ha
Runoff+barrier +mulch	4,510	10,800
Flat-surface control +barrier	1,970	10,100
Flat surface control +barrier +mulch	2,380	10,400
LSD (0·05)	834	1,290

Fig. 2 illustrates the comparative

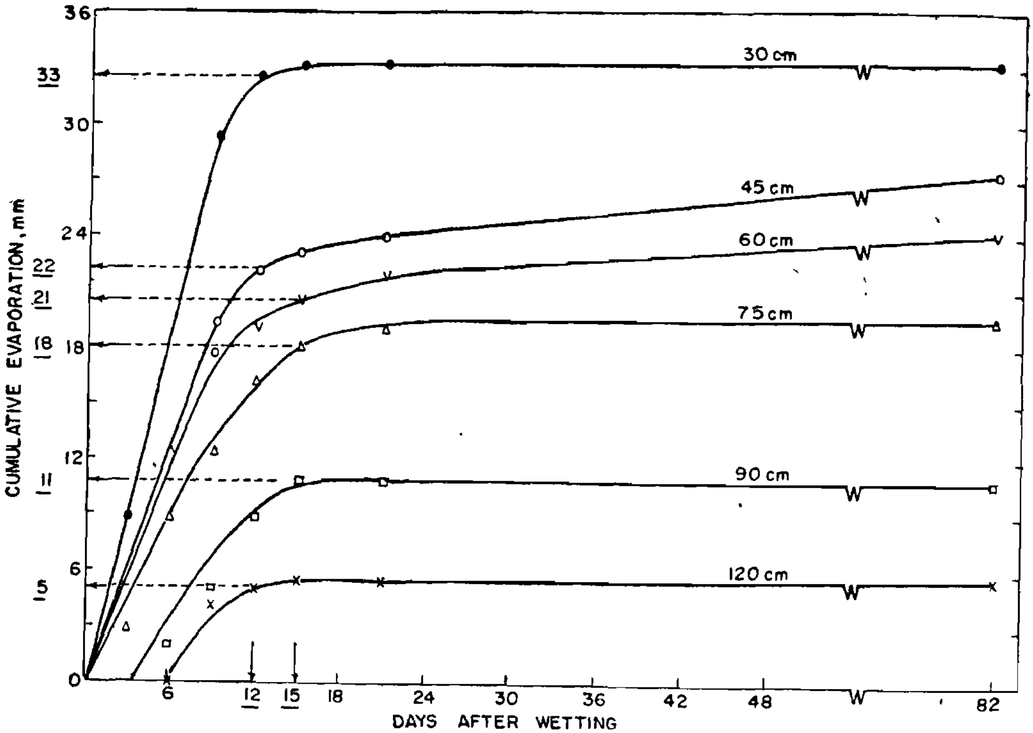

Fig. 2. Comparative evoporation for various depths from bare surface of loamy sand in 82 days (S.D. Singh, 1976—unpublished)

evaporation for various depths from the bare surface of the loamy sand for an 82-day period from 4 March to 25 May 1976, and emphasizes the importance of selecting a reasonably optimum depth of asphalt floor where mechanical feasibility and the evaporative control are at a compromise. The major evaporative losses ranging from 18 to 33 mm took place from the first four depths, 12 to 15 days after wetting, but were less from depths of 90 and 120 cm. After this period, the evaporation, especially 75 cm. below the surface, was of least practical significance. From these data the ideal depth of AMoBar would be around 90 cm below the surface. Much of the larger water storage deep in the profile is safe from evaporation, is conducive to deep root proliferation, delays the arrival of the drying front to the site of the perched water-table, but has one and the only one disadvantage of high power requirement, not so difficult to meet. International Harvester Company of the U.S.A. has developed a machine (see Figure on p. 9 of AMoBar information bulletin, AMOCO, Chicago) which lays a 2.3 metre-wide barrier to a predetermined depth, or covers one hectare in 2.5 hours.

Agronomic practices concomitants of AMoBar

(a) *Insulative mulches*: The evaporation rate-amount advance illustrated in Fig. 3 suggests the importance of integrating insulative mulches with AMoBar especially "early" in the season. Perhaps warranted by a similar situation, the Hawaiian planters have been using black paper and plastic mulches in the case of pineapple since early 1920's, since this crop uses the maximum amount of water when the plants are small and direct evaporation from the soil is great. However, in view of the "self-mulching" action will this integration be necessary? In "sand", certainly not. But as may be seen from Fig. 3, a distinct possibility for AMoBar-mulch integration does exist in "loamy sand", but only for a short period early in the season. For the evaporation from the highest mean rate of 10.3 mm/day two days after wetting declines to a 0.7 mm/day 19 days after, and the total loss is 107 mm. From this to the 82-day period, the total loss is 6 mm/day, at a mean rate of 0.1 mm/day, a rate hardly of any practical significance.

Also shown in Fig. 3 are the evaporation (in regular line) from a wheat field for an eight-day period from the date of planting on 25 November to 2 December 1975, and the ET (in broken line) for 14 days thereafter. During this cool period also, the evaporative losses are high when the plants are small. It is obvious from these data, though limited, that the insulative mulches as a companion practice to profile stratification is short-lived, early in the season until the crop cover is<50% complete. Once the crop cover is>50% complete, evaporation remains a negligible fraction of the total ET. Mulching over the "full" crop season then hardly serves its intended objective.

Plastic is an effective barrier against evaporation, but is subject to heavy photothermal deterioration and damage by aerodynamic uplift. Necessity of this kind of insulative mulch for the short period early in the season may be advantageous. After use for a month or so, it may be collected and stored for subsequent use. Over seasons, the cost, as a result, may be low but the initial cost requirement (for 90% cover) is about $ 1,379/ha. So, for all its success, the benefits from the additional moisture

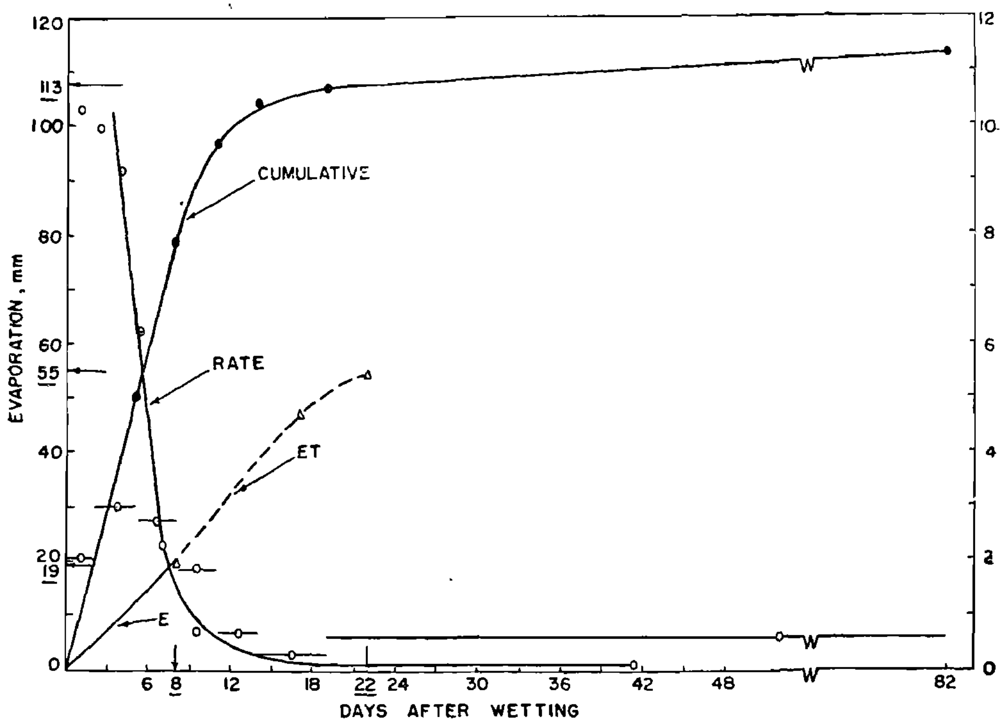

Fig. 3. Rate and cumulative evaporation from a wheat field after harvest over an 82-day period (S.D. Singh 1976—unpublished)

conserved because of mulch must be sufficient to pay for its cost. But as seen from the data in Table 2, the quantum of extra yields due to the integration of organic mulch with bentonite barrier will seldom pay for its cost. It is also evident from yield differences due to mulching under the runoff concentration system and flat-surface control that organic mulch even at 4 tonnes/ha was not an effective barrier against evaporation. With insulative plastic mulch (90% cover), the yields may be much greater on the mulched plot because of most of the water use through transpiration on the mulched plots early in the season. However, the additional gain from the integration of such a practice with AMoBar on a coarse-textured soil of this region remains to be seen.

(b) *Higher plant densities*: Higher plant density has been a shot-gun easy-to-control practice known for its potential in enhancing transpiration relative to the non-growth-related evaporation since the date it was originally proposed by Chang (1968). One should not be mistaken that a twofold increase in plant density will require twice as much water. The consumptive use remains about the same or increases only slightly (Ram Niwas, 1975), whereas the yield increases up to the density where the compensation in individual and group performance of plants is compromising (Table 3). This is how the "traditional approach" of Viets (1965) and Jensen (1972) seeks to maximise the efficiency of irrigation by increasing yield without changing or increasing slightly the seasonal ET.

Later, Shmueli (1973) proposed the term "optimum irrigation efficiency" which by definition reaches where the ratio of yield (Y) to the seasonal water applied (Wa) is maximum. But he emphasizes the importance of the range of optimum ET which can ensure maximum yields and not necessarily the maximal (Y/Wa) ratio.

Considering mathematics, it is clear that if (Y/Wa) ratio remains constant or either increases or decreases in any steady fashion with a change in the seasonal ET

Table 3. Yield Y, ET, Y/ET, and yield to irrigation water ratio (Y/Wa) of the wheat crop at five populations. Water and N fixed at 56 cm and 150 kg/ha

Seed	Yield	ET	Y/ET	Y/Wa
kg/ha		cm	kg/cm	
75	3,554	58·8	60	63
95	4,342	60·6	72	77
125	4,717	62·0	76	84
155	4,740	62 5	76	85
175	4,904	69·7	70	88

over such a range, the maximum irrigation efficiency can be obtained. But it may be recognized that in the case of most crops, there will be a disproportionate fall in the yield corresponding to ET less than the "optimum", and after increasing at a diminishing rate up to the genetic maximum, the yield will not increase by ET increase beyond the ETmax. This kind of situation is noticed in the data illustrated in Table 3. As may be seen, the seed-rate optimal for the leaf-area index closest to the ideal we want for the efficient use of water ranges from the "optimum" (125 kg/ha seed in this case) pinpointed by the "old approach" to a level where (Y/Wa) ratio is maximum (i.e. at 175 kg/ha seed). But the added benefits from each added unit of seed input above the "optimum irrigation efficiency" defining term is preponderantly overgeneralization of the "old approach" to the problem of increasing irrigation efficiency.

Higher plant densities may be helpful in improved water management also through a control on water flow below the root-zone. Fig. 4 shows water distribution under three population densities of tomatoes, viz. 48, 96, and 192 plants per 12-metre length of drip irrigation lateral, each receiving an equal amount of water based on the daily crop ET demand. Water distribution in the pro-

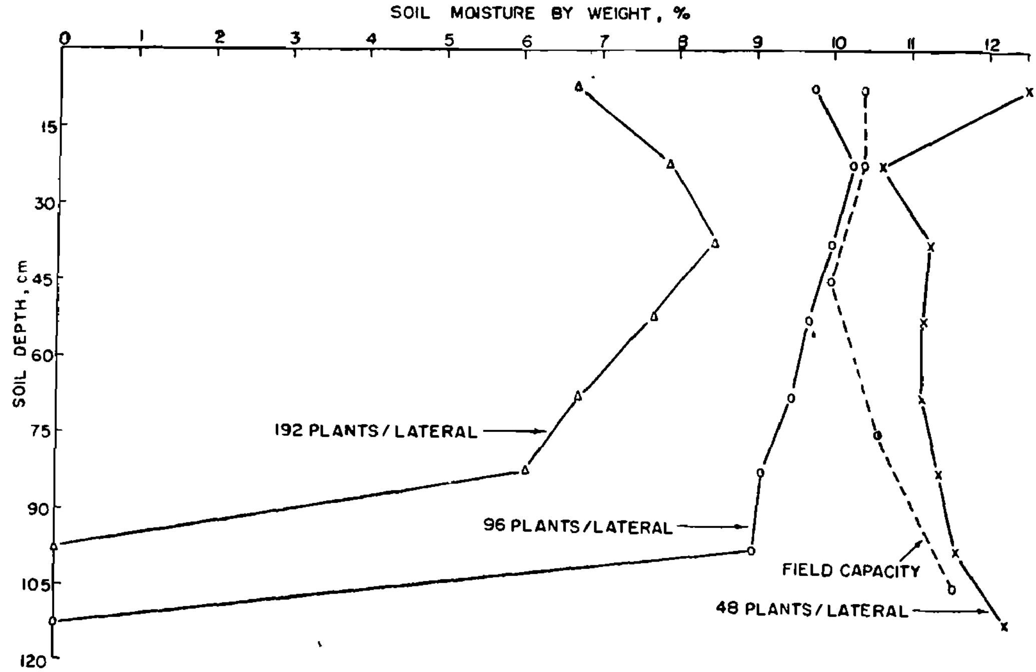

Fig. 4. Effect of plant densities on water distribution in the root zone of the tomato (S.D. Singh, 1976—unpublished)

file pertains to the stage tomatoes were finally picked. In each case, the plants had to share the same amount of finite water-supply. As may be seen from three curves, the low-population crop exerted a less use thrust on added water. The net result is that soil moisture at all depths was never reduced to values where drainage could cease. On the contrary, where a large number of plants had to share the same amount of finite water-supply, the soil moisture at all depths below 45 cm was reduced to values where no drainage could occur. Dry soils below 105 cm on 96 plants/lateral plot, and below 90 cm on 192 plants/lateral plot further confirm that no water was lost from the potential root-zone. This mechanism may not be applicable to AMoBar, but the control on water flow below the root-zone by a higher plant density may be a complementary practice to bentonite or pond-silt barrier that allows a sizeable percentage of deep drainage.

B. Concept of Modest Irrigation

The ratio of crop ET to applied water should approach unity for maximum efficiency in water use and application. If it were true, the ET to applied water ration would always be unity and follow the path shown in broken line in Fig. 5. As seen from ET-applied water, yield-ET and yield-irrigation relations superimposed on yield-to-field water-supply relationships in Fig. 5, this ideal can be achieved by irrigation in the low range of application. As we approach the maximum ET to attain the maximum wheat yield, the non ET water use increased, the ET to applied water ratio becomes less than unity, and the efficiency of water use declines. On the other hand, when water application is limited up to a certain level (56 cm in this case) below that required for the maximum yield, the non-ET water use is eliminated and irrigation efficiency becomes 100%. It seems that there is an optimum yield-water relationship that can be employed to the problem of water distribution in each of the three common situations encountered, i.e. the attainment of the greatest yield per unit of land when the land is limited, the greatest yield per unit of water when water is short or expensive, and the "lowest acceptable yield" when benefits from the limited available water-supply to the greatest number of farmers are to be assured.

From the foregoing account the application of the much-emphasized concepts (Hillel, 1972) of maximizing plant response by making water completely non-limiting to growth in the arid region is a great fallacy. Let Hillel not lose sight of the fact that the "maximum" or "most profitable yield" concept (89 cm) of applied water for the maximum wheat yield of 5,460 kg/ha, or 73 cm of it to maximize the profit at 5,266 kg/ha yield level (see Fig. 5), is applicable to the area of water abundance and limited land. Either of 89 or 73 cm of irrigation falls in the upper end of the ET applied water relation

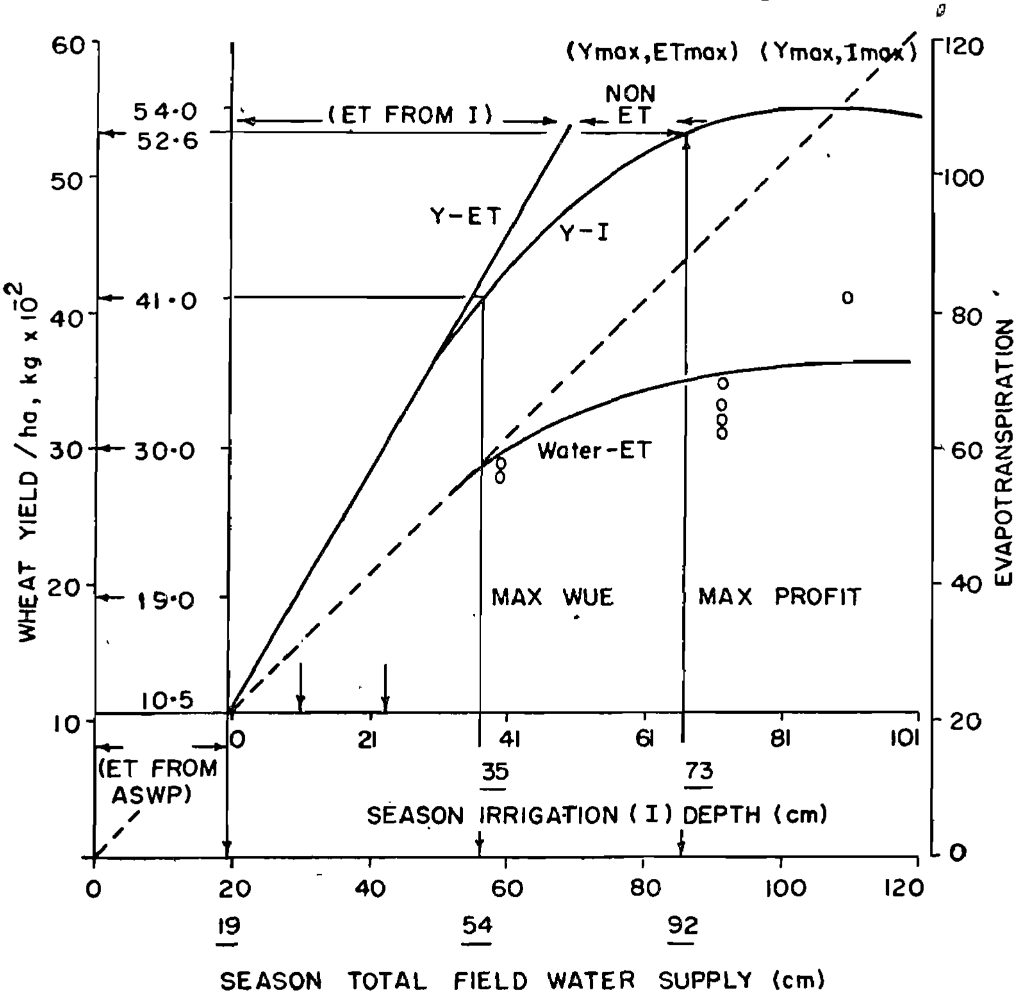

Fig. 5. Applied water-ET, yield-ET, and yield-irrigation relationships plotted within yield-field water supply functional relationship

where the non-ET water use is great. Have we so much water to waste? Certainly not. Therefore in the arid areas, the objective is to increase production per unit of water and not per unit of land, since the water and not the land limits production. Here, a lower average yield from a modest depth of irrigation on a large area can result in higher total benefits than by most profitable yields from a small area. In this case, one may be interested in the use of water at a maximum water-use efficiency point (in this case, 35 cm of water, and a yield of 4,100 kg/ha or 1 kg of wheat for 0.85 m^3 of irrigation water), or to optimize yield-water relation that attempts to maximize yield from the least number of irrigations with minimal depth of seasonal irrigation water. This is respectively what the "traditional" or "optimization" approach is all about.

TRADITIONAL APPROACH TO THE PROBLEM OF OPTIMUM WATER USES

The agronomic aspect of water use by a crop is generally described in terms of water-use efficiency. Since it is a ratio of $\frac{\textit{harvestable yield}}{\text{Crop ET}}$ its value can be increased either by increasing yield or by decreasing the ET. The "traditional approach" seeks to increase the water-use efficiency by increasing the yield with little change, if any, in ET. So if we assume that ET is constant or relatively so over the range of management, the defining equation can be written as: Water-use efficiency = constant × yield. Hence the traditional approach seeks to increase the water-use efficiency by seeking ways of improving yields. Much of the information of this kind is given by Pendleton (1965). Emphasis here will be on some of the important plant and cultural factors of immediate practical concern.

A. Crop Species and Varieties

Crops differ in respect of their growing season, root-system, density, spacings, height, leaf orientation, reflection coefficient, photosynthetic efficiency etc. Because of these differences, they differ widely in their efficiency to produce dry matter and water use.

Crop species of high potosynthetic efficiency use water efficiently. For example, C_3 plants (pulses) have a low rate of photosynthesis, so they have a low water-use efficiency. The C_4 (millet and sorghum) plants, on the contrary, have a higher rate of photosynthesis and their water-use efficiency is twice as high. Yet much headway in this aspect of plant improvement remains to be made. The additional scope lies in increasing leaf reflectivity, although numerous studies indicate minor species differences regarding their leaf reflectivity.

Some workers have tried to relate ET requirement to plant height. But very little conclusive field evidence is available to support that a tall variety requires more water than a short one. Take, for example, wheat. In the case of this crop, there has been no difference in ET (for any given irrigation treatment) between the tall and the dwarf varieties (Singh *et al.*, 1970; Shimshi *et al.*, 1973). It means that the higher yields obtained from a dwarf variety does not necessarily require more water. Nor does a short-statured or dwarf variety transpire less than a tall variety. A more efficient use of radiant energy, a better conversion of dry matter into grains, and a continued response to higher fertility levels are all set for higher yields and thereby a more efficient water use by a dwarf variety.

Some morphological characters are reported to influence the water-use efficiency. The awned varieties of wheat and barley perform, in general, better than awnless varieties, possibly because the awns result in cooler canopies owing to increased sensible heat transfer. Significant yield breakthroughs are being sought by changing the shape or morphology of our crop plants. For example, the daily canopy synthesis is much higher in an erectophile than in a planophile canopy. The optimum leaf-area index is between 4 and 7 for erectophile and 2 for planophilic canopies; so the transpiration efficiency is much greater in the case of an erectophile canopy. Yet far more work is needed to understand clearly the whole dynamics of soil-water-plant-atmosphere to predict the water-use efficiency of crops with contrasting leaf sizes, shapes, and angles.

B. Agronomic Practices Relating to Water Use

Time and depth of sowing

The objective in the adjustment of sowing time and depth is to ensure a proper temperature and other physical conditions of the soil favourable to seedling emergence, vigour and finally the crop yield. On a broader scale, such adjustments are done with a view to shortening the growing season, match growth and development either with the rainy season or with a cool period or to avoid cropping in the season of the highest ET. Implications of these aspects on yield and water-use efficiency are well known and need not be elaborated.

Level of management

The management factors have an important bearing on the efficient use of limited water. In fact, controversy abounds in agronomic literature regarding the adjustment of fertilizer application and plant population to suboptimal irrigation water. Some agronomic literature seems to suggest that when the water-supply is short, the crop yields will not be affected greatly if fertilizer applications and seeding-rates are maintained at those appropriate for optimal water availability. Other evidences, on the contrary, suggest the potentially higher yield realization incidental to smaller nitrogen and smaller-seed-rates under suboptimal water availability.

A better knowledge of the interaction among fertilizer, water and the seeding-rate is needed to determine the reasons for such divergent responses, now reported. A study along these lines by Ram Niwas (1975) shows that under suboptimal water-supply (29 cm in his case), the production of wheat with a low level of nitrogen (61 kg/ha) and a seed-rate of 75 kg/ha was 1916 kg/ha. When the nitrogen application and seeding-rate were maintained at levels appropriate for optimum water level (150 kg of N and 125 kg/ha seed), the yield was 3,155 kg/ha. This essentially lends strong support to the view that crop yields can be increased greatly by combining the optimal levels of fertilizer application and seeding-rate with short water-supply.

His study further indicates that when water is a nonlimiting factor water-use efficiency in relation to plant density and fertilizer application depends on the effect of these inputs on the yield-ET relationship. As long as the change in the yield relative to ET is greater, the water-use efficiency increases. After increasing at a diminishing rate up to a point of genetic maximum, the yield remains constant or decreases, whereas the relative change in ET is gradual up to ETmax. The water-use efficiency, as a result, attains the maximum value at the point of input use (150 kg of N and 155 kg/ha of seed in his case) where yield is maximum. The moment the yield diminishes from its point of maximum, the ET still remains at ETmax or becomes inflated owing to excessive evaporation by frequent irrigation early in the season or at maturity, the water-use efficiency begins to decline.

Contrary to common belief, more fertilizer requires more water, Table 4, however, shows that a wheat crop twice as large will not require twice as much water. Its ET is about the same or is only slightly more. Optimally, a fertilized crop produce much higher yield per unit of water than a poorly fertilized crop.

OPTIMIZATION APPROACH TO THE USE OF WATER

There are two basic assumptions in the traditional approach: (1) the complete avoidance of ET deficit, and (2) additional water application for leaching down salts. Having assured that water is a nonlimiting factor in plant growth, it seeks ways of improving yield with little change, if any, in crop ET.

Table 4. Yield Y, ET, and Y/ET of wheat for five nitrogen application rates. Water and seed-rate fixed at 56 cm and 125 kg/ha (Ram Niwas, 1975)

Nitrogen	Yield	ET	Y/ET
——kg/ha——		cm	kg/cm
0	2,332	60	39
61	3,984	60	66
150	4,717	62	76
239	4,535	62	73
300	4,532	65	70

The water-use planning in accordance with the doctrine of complete avoidance of water deficits and reduction of irrigated hectareage in short water-supply years for fully meeting the water requirements of each hectare and additional water need for leaching down the salts in water-deficient region is inadequate. We propose a new water-planning premise which assumes that it is possible to apply water less than the seasonal ET. No additional application of water is necessary for leaching down salts. It assumes that under conditions of poor-quality irrigation water use, the subsequent rainy season will remain one or two seasons fallow, depending upon the amount of rainfull received to leach down the salts accumulated during the irrigation season.

A. Optimal Irrigation Programme

To apply a volume of water smaller than ET requires that, the loss in yield should be minimal. For that reason, it requires to increase the ET from the least number of irrigations and the least depth of seasonal irrigation, provided the growth-stage effects are controlled. Hence a quantitative knowledge of the growth-stage effects on yield is essential. Because once the critical periods in the life-cycles of various crops are identified and sequenced in order of relative sensitivity, it would be possible to generate an irrigation programme which will impose (warranted by short water-supply) an ET deficit within the limit of tolerance in stage(s) less sensitive to water and avoid, as far as possible, the occurrences of the ET deficit during the critical stage.

Ram Niwas (1975) has identified the periods sensitive to water in the life-cycle of the wheat crop. According to him, the booting or heading stage is most critical in wheat, followed by the period from flowering to grain development, and the active tillering stage. An early period of growth is the least sensitive. The ET deficit, 10 to 18% in vegetative stage conditions the crop to tolerate 30 to 35% ET deficit in the critical booting or heading stage. Similarly, the allowable ET deficit introduced in the booting or heading stage hardens the crop to tolerate as much as 39% ET deficit during the period from flowering to grain formation. The flowering stage in mustard, a week before flowering in sunflower, and the normal period of branching and flowering or grain development in safflower are most sensitive to water-supply.

For the number and depth of irrigation to be the least, our optimal irrigation programme must be developed with due consideration to all sources of crop water-supply from which ET is derived. We propose to deal with this point taking the wheat crop as an example.

As indicated earlier, ET is derived from irrigation, available soil water at planting, and the growing-season rainfall. Rainfall expectations during the growing season of wheat is nil. Only stored soil moisture remains to be considered in the optimal programme. To include the contribution of stored soil moisture to ET in the model, it is necessary to determine the genetic potentiality of the root-system to explore the soil profile and extract water from there under unirrigated-plot conditions (designated ETbasal). Changes in the ET basal as well as in the ETmax are to be expressed as a function of time, so that the irrigation is optimally timed. The upper limit to water uptake in response to root growth requires that neither the soil depth nor the structure is limiting to root growth, nor should there be any interference by rain or intermittent irrigation.

In a large part of the sandy arid plains of Jodhpur, the soils are sufficiently deep (120–150 cm). Being light in texture, their physical conditions are seldom likely to limit root growth. The only requirement difficult to meet in this area is the estimate of the upper limit to water uptake from non-irrigated wheat plot, for over the entire sandy arid belt of Rajasthan wheat cultivation under unirrigated conditions is not possible. Therefore, a plot was simulated to represent non-irrigated wheat by a preplant irrigation to bring profile moisture to field capacity.

The time functions of cumulative ETmax and ET from available soil water at the time of sowing are combined in Fig. 6 with a view to showing the importance of ET derived from the stored soil water in meeting the water needs of the crop, reducing the seasonal-irrigation requirement, the ET deficit expectations, and to optimize the irrigation programme in advance of the season.

Fig. 6 shows that the ET from the available soil water at the time of sowing (from the plot simulated to represent non-irrigated conditions) continued to meet the water needs of the crop all through the season. The peak supply was during the period of tillering to the early booting stage. From then on, until maturity, the contribution of ET from profile storage was only a fraction of a centimetre. Thus the greatest need for ET from irrigation coincided with the peak water-use period. The knowledge of ET deficit expectations emergent from time functions of the cumulative maximum ET and ET derived from the available soil water at sowing allowed the development of optimal irrigation programme for wheat. An optimal irrigation programme is that which reduces the number of irrigations, projects their dates, and reduces the depths of all-season irrigations through a better understanding of the open soil-water storage capacity in the root-zone when irrigations are applied and they are terminated timely.

Furthermore, the optimal irrigation programme with limited water requires a cut in that irrigation which contributes only a little to the objective functions, ET deficits, as far as possible, are eliminated at sensitive stages, and some ET deficits are imposed in stage(s) less sensitive to water. The programme of imposing the

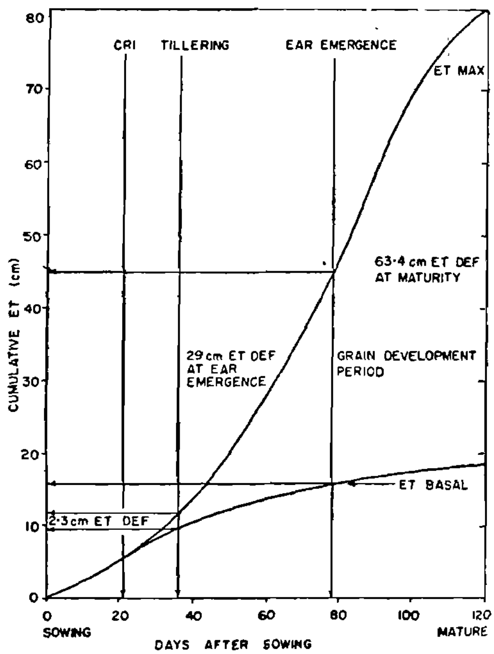

Fig. 6. Time functions of cumulative ET max and ET basal averaged over 1971–73 to quantify ET deficits at various stages of the wheat

ET deficit must remain within the limit mentioned earlier, i.e. the tolerance when there has been no prior ET deficit and the tolerance due to conditioning by prior deficit.

Fig. 6 shows that our climate sets up an ET demand (ETmax) of about 82 cm in a certain time sequence over the season. It further shows that the exploitation of soil water by root growth into the profile which was at the field capacity at the time of sowing resulted in an actual ET (ETbasal) of 19.0 cm, again in a certain time sequences. Thus the ET deficit to be satisfied by an irrigation programme intended to achieve ETmax is 82–19= 63 cm, and, of course, this deficit also occurred in a certain time sequence which was dictated to by the sequence of ETmax ETbasal. The optimal programme must provide 63 cm of ET to be derived from irrigation water, with the least number, and with the minimal depth (in the light of the built-on unevenness of water distribution which characterizes our irrigation method) of irrigation water. Such irrigation, barring the last, must refill the soil profile (to assure ETmax at every point in the field, otherwise the unevenness of water application would leave some spots with excess water where it may be subjected to loss through deep percolation). The final irrigation may be given at any time the water-storage capacity exceeds the needed depth of water with which to finish out the season at the ET-max rate. So, though unevenly distributed, all of the final irrigation will be stored (storage=irrigation). No residual moisture remains.

Of gross irrigation water depth in storage immediately following any irrigation, only 70% can be utilized before the actual rate or ET (ETbasal) will fall below the ETmax rate. Additionally, some assumptions and definitions will be considered in order. The goal of programming irrigations is to increase the yield, or to increase the irrigation efficiency. In optimization at hand, the irrigation efficiency will be defined as the percentage of irrigation water used in ET. The open soil-water storage capacity within the root-zone at any irrigation will be expressed as irrigation. It is assumed that the depth of irrigation water actually stored=the storage capacity (except the final irrigation). Thus the irrigation water stored or the storage capacity=1, and the minimum depth of irrigation which can refill the root-zone=the storage capacity+deep percolation due to the maldistribution of water. The dispersion of water depths infiltered during irrigation will be assumed to be 2 cm of irrigation water, without any allowance for runoff, a non-existent factor in this case. The water depth infiltered during irrigation will be taken to equal percolation, i.e. the amount of irrigation water that will seep down when the root-zone is refilled.

The optimization is based on many assumptions and definitions; therefore, it may be considered the first approximation. With the availability of more data, it will be extended. At this stage, it is intended simply to suggest some considerations required for the optimization of an irrigation programme when water-supply is limited.

With these considerations and limitations, an optimal irrigation programme has been developed (Ram Niwas, 1975). Part of the data set forth in Table 5 show how such optimal programme projects the number, dates and depths of all-season irrigation, pinpoints irrigation termination, eliminates those units of irrigation which are contributing the least to the yield per unit of applied water, imposes ET deficit at less sensitive stage (s) of growth, thus offering opportunity for the achievement of maximum ET, hence the maximum yield, with the least number and the least depth of irrigation water and reducing yield losses owing to the limited use of water. As for example, irrigation required for the maximum yield (5,430 kg/ha) of wheat at Jodhpur=84 cm. The uses of 40 and 20 cm of irrigation optimally planned produce 4,724 and 3,668 kg/ha of wheat respectively. This means that against 52 and 76% reduced uses of water, the losses in yield respectively are merely 13 and 32%. The optimization approach seeks to fulfil this objective.

B. Concept of Extensive Irrigation

The above water-planning philosophy, more or less, corroborates the concept of extensive irrigation which seeks to apply a small quantity of water over a large area rather than a large quantity of it over a small area. How this new concept of irrigation will enable considerable increase in production from the same amount of applied water and provide eventually two

Table 5. Optimal irrigation programme for wheat 'Kalyansona'

Season IRR	Reduced water use	IRR days after 21	40	54	68	78	90	100	IRR Eff.	Yield reduction	Total yield
cm	%	cm							%	%	kg/ha
84 1 (IRR max.)	nil	7 2	10·4	11·8	13·2	14	14·9	12 6	75	nil	5,430
40·0 (IRR med.)	52	—	2·5	10	5	10	12 5	—	87	13	4,724
20·0 (IRR low)	76	—	2·5	—	5	7·5	5	—	95	32	3,668

to three times more rural employment and opportunity for the distribution of social benefits can be judged from the following production figures shown in Table 6. Extensive irrigation will mean a smaller addition of salts per unit area per irrigation, besides the least chances of salts filtering up from the perched brine to the surface.

Table 6. Production for a given water quantity used over different areas

Crop	Water used (cm)	On area (ha)	Production (kg)
Wheat	84	1	5,500
		3	9,100
Hyb. *bajra*	25	1	4,200
		4	10,300
Grain sorghum	28	1	4,400
		2.5	6,400
Sunflower	50	1	1,600
		2	2,700
		1	1,100
Mustard	25	1.5	2,000

C. Optimal Allocation of Water to Crops

The recommended irrigation practices in respect of each crop may be important in their own right, but the water allocation for the farm unit as a whole confronts the farmer with the decisions loaded with high prices, product and input variabilities. Suppose that the crops, e.g. wheat, mustard, sunflower and safflower, are competing at the same time for finite water resource on a farm. How much area of what crops be allocated for the maximum gross returns from a given level of water-supply? What impact will the severe restrictions on fertilizer availability have on gross returns? An attempt has been made to answer such questions of the farmer.

Twelve optimum farm plans have been prepared for twelve alternative situations arising from a multiple of three water-supplies (tube-wells having 2, 4, and 10 thousand gallons/hr discharge) and four levels of fertilizer availability, i.e. unrestricted fertilizer supply (UFS), and 75, 50 and 25% of it. As seen from the optimal farm plans shown in Table 7, under all levels of water availability and unrestricted use of fertilizer as well as 75% of it, the area under wheat, mustard, and safflower should be respectively 38, 31 and 31% (mustard=safflower) of the total area that could be commanded by any of the above tube wells. If the supply of fertilizer is reduced to half or even less of the unrestricted use, the area under wheat and mustard respectively comes to 55 and 45%, safflower being eliminated from the plan. Sunflower does not find place in any of the 12 optimum farm plans.

In the final analysis, the input combinations most optimum for wheat and mustard under the optimal farm plan, when both water and fertilizer constrain production, will be like the one shown in Table 8. Further, it has been established that such optimal nitrogen plant-

Table 7. Optimal allocation of water

Crop	% of command area
UFS and 75% of UFS	
Wheat	38
Mustard	31
Safflower	31
50% and 25% of UFS	
Wheat	55
Mustard	45

density combination increases yield with a slight increase, if at all, in ET. This observation indicates a reduction in irrigation water required per unit production and the production of the quantity of the commodity needed with less total water.

Table 8. Optimum farm plan when both water and nitrogen constrain production

Crop	Water	Nitrogen		Density
	cm	kg/ha	kg/ha	cm (row× plant)
Wheat	45	105	125	—
Mustard	18	30	—	40×20

D. Efficient Water Use by Drip Irrigation

Finite water resource in arid and semi-arid region has aroused interest in applying water by a newer irrigation method known as the trickle or drip irrigation. The system has shown yields far in excess of what at one time was thought possible with conventional irrigation. Compared with sprinkler per 5-day cycle and furrow irrigation, a 45 to 47% increase in yield on long gourd, 21 to 38% in that of round gourd, 10 to 22% in water-melon, and a little yield gain in ridge-gourd with drip irrigation indicate that daily drip irrigation has a potential to increase the yield of most, if not of all, vegetable crops, with nearly 2 times better water-use efficiency and the installation cost (the only additional expenditure on drip system) pays off in 1 or 2 seasons (Singh and Singh, 1976). Further, 20 to 32% less yield of water-melon and round gourd with daily sprinkler irrigation than with drip irrigation shows that on loamy sand in the hot arid belt daily irrigation is advantageous by using the drip method and not necessarily with a sprinkler.

The evaluation of the drip method of irrigation with sweet and saline water on the yield of potatoes and tomatoes has further shown that for identical yields it requires 50% less water than furrow irrigation(Singh *et al.*, 1976). This method of irrigation may, therefore, be a positive means of saving 50% of water in the production of potatoes. With drip irrigation, saline water of 3,000u mhos/cm is not so much a limiting factor in yield but at 10,000 u mhos/cm it causes a 91% reduction in yield of potatoes and only a 35% reduction in that of tomatoes. These results are consistent with the relative sensitivities of the two crops to poor-quality water.

Salts are found to be concentrated in the surface 15–20 cm of the soil at the mid-point between emitters and towards the periphery of the wetted band, with a distinct salt-free zone beneath the emitter to the full depth of the soil profile. This accumulation pattern derives importance from the fact that salts removed from the active root-zone accumulated in the surface soil at some distance away from the plant would be positionally unavailable for causing injury to plants in all those areas where the in-season rainfall is non-existent. However, in areas experiencing the growing-season rainfall, this pattern of salt accumulation would become a matter of serious concern. Obviously. it would either impose a limit to the use of brackish water by using the drip method in areas with the growing-season rainfall, or else a package of special management practices will be necessary.

The drip method of irrigation has originally been designed on the "one plant, one dripper concept", i.e. providing a dripper near each plant. Because of this arrangement, the initial cost is high. However, the cost reduces to half when a 25 cm square or equilateral planting of vegetables is integrated into the drip system. In addition, a 50% saving in water occurs.

IMPROVING EFFICIENCY OF PRECIPITATION

The stored soil water is converted into ET 100%. Whereas the conversion of rainfall, a primary source of stored water, into ET will be closed 200%, provided the known mechanical measures for runoff control, tillage technology for higher water intake, organic amendments for water retention after it enters the soil, profile stratification with layers that impede drainage, good germplasm and protection against insects and disease, adequate nutrient supply, etc. are all integrated into the system under consideration. Nevertheless, in low-rainfall years, though the stored water will be converted 100% into ET, it will not be sufficient for crop consumptive requirements; however, so crop failures and zero rainfall efficiency are common occurrences in arid and semi-arid regions.

There are two aspects of this problem. A sure approach to rectify it is supplemental irrigation. Work by the author shows a rainfall supplement by sprinkling 25 cm of water over four hectares of hybrid *bajra*, and 27.5 cm of water over 2.5 hectares of grain sorghum resulted in the total production of 10,332 kg of *bajra* and 6,385 kg of sorghum respectively. Where any supplement to rain was not made, the crops succumbed to drought and rainfall efficiency declined to zero.

Another way, presumably as sure, is the runoff concentration that is also irrigation. A variety of runoff concentration methods have been used by workers all over the world. To provide more runoff as irrigation water by the concept and method suited to this summer-rainfall region, an innovative technology has been developed (Singh, 1976; his Fig. 1). From the catchment to the cultivated-area ratio of 0.5, each hectare of cropped area receives 23 to 108 mm of runoff as irrigation water from the catchment in addition to 117 to 528 mm from direct rain. The additional low tension water results in increasing and stabilizing crop yields, in lowering the risk of crop failure, in saving inputs of production, and, above all, in making the best of every rain drop that falls on the farm.

Occasionally, the rainfall exceeds the profile storage, more frequently in shallow sandy-loam soil of the region. When water received during the period of surplus cannot be stored in the soil profile for use during the deficient period, at least it can be conveyed to a reservoir located somewhere at the lowest point on the catchment and recycled as drought-evading irrigation. For the requirement of a slope, such a practice has a locational feasibility near the foothills. However, by removing the permeable top soil and suitably shaping it, the author proposes the construction of "roaded catchment" on the flat surface. The technique will provide about 5 to 10% slope on the "roads" for runoff and some 0.5 to 1% slope for runoff flow from ditches to the reservoir.

CONCLUSION

The problem of a volume of water less than the seasonal crop evapotranspiration (ET) may be resolved at least in two ways. First, the "traditional approach" to the problem of efficient water uses. This approach seeks ways of improving crop yields with little change, if any, in the crop ET. Basic assumptions inherent in this approach are the replenishment of full ET demand and the application of additional water for leaching. An improvement over this approach is the "optimization approach" which obviates the need for water application for leaching down salts. In addition, it is possible to apply irrigation water less than the crop ET and simultaneously reduce yield losses by an optimal irrigation-planning that seeks to impose optimally sequenced ET deficits at less sensitive stage(s) and to avoid, as far as possible, the water deficits at the critical stage. The optimal programme considers all sources of water from which ET is derived and thus fulfils the maximum ET with the least number and the least depth of irrigations. Embedded in the "optimization approach" is the concept of extensive irrigation and a newer method of irrigation known as the drip irrigation. The two have special promise in squeezing the best out of the low total water-supply.

Increasing the amount of water storage per unit volume of soil by stratifying the profile with asphalt moisture barrier, and the removal of the non-ET water use by employing the concept of modest irrigation are other two prongs of water-use optimization strategy. The integration of insultative mulches "early" in the season, high plant density, adequate supply of plant nutrients, and good germplasm into these practices will further brighten the future of the optimization approach in solving the problem of efficient water use in water-deficient regions of the world.

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26

ARID HORTICULTURE

O. P. PAREEK

THERE are hardly any orchards in the arid regions in spite of a great potential for fruit-growing (Pareek, 1975). The characteristic soil and climatological features of these regions are most favourable for the production of certain fruits and offer conditions for the development of a distinct fruit quality (Mann and Pareek, 1974). These features, however, restrict the choice of fruit crops for such regions and also necessitate the use of special growing techniques for their successful cultivation.

Selection of crops

The rainfall in the hot Indian arid zone is very low and is confined to the period from July to September, with 9 to 21 rainy days out of 12 to 30 rainy days in the whole year, resulting both in soil-moisture stress and atmospheric water stress to the plants after the rainy season. After April, the vapour-pressure deficit is more than 24 mb and exceeds 30 mb during May and June. The fruit crops selected for cultivation in these regions must be such that their maximal growth period falls during the period of maximum water availability in the soil and low vapour-pressure deficit in the atmosphere. Ideally, the most part of their reproductive cycle, i.e., the period from flowering to fruiting, must also fall during this period and the fruit-ripening must be completed before the onset of the dry summer. Fruit crops, e.g., the *ber*, pomegranate, guava, custard-apple, *aonla* and *karonda*, conform to this pre-requisite. These crops can be grown, with or without the use of runoff concentration or with water-conservation systems or both depending upon the average annual rainfall of the region.

The fruit crops having deep root-systems have the capacity to draw water from the deeper layers of the soil profile and would, therefore, be capable of surviving droughts. It must be appreciated that whereas, on the one hand, desert soils are very poor in water-holding capacity, they are also generally shallow and are underlain with a *kankar* layer of 70-100 cm thickness at depths varying from 10 to 150 cm. Fruit crops capable of striking their roots in and through this layer are, therefore, most adaptable to desert conditions. Roots of *Zizyphus rotundifolia* rootstock (having *Z. mauritiana* as the scion) penetrated through a 100-cm-thick *kankar* layer (Plate **o**). Some crops, for example, *ber* and *gonda* (*Cordia myxa*), conserve moisture by shedding their leaves during summer. This is a very useful drought-evading mechanism. The conservation of moisture is also brought about by certain water-binding chemical constituents in the tissues, resulting in high 'bound water' contents, e.g., in the case of fig. Other xerophytic leaf characters, e.g., a thick cuticle, a coating of wax on the surface, hairiness, sunken and covered stomata, help to minimize the loss of water through transpiration. Fruit crops, e.g., fig, *phalsa*, *ber* and *Cordia myxa* have such characters.

There is another group of fruit crops

which can be profitably grown in the arid tracts having irrigation facility, e.g., date-palm, papaya, *phalsa*, mulberry, citrus fruits (kinnow mandarin, musambi, malta, sour lime and grape fruit), grape and mango. These crops require dry and hot summer for the development of good-quality fruits. At present, hardly 4,000 ha and 1,000 ha of such orchards are present, in the arid regions of Rajasthan and Gujarat respectively. The cultivation of these fruits will become popular wherever irrigation facility will come up, particularly from canals. Date-palm, pomegranate and *Cordia myxa* can tolerate high salinity in irrigation water and, therefore, can form an important component of the crops to be grown under the command of a large number of brackish-water wells found in these regions.

Rocky and gravelly wastelands are very suitable for the systematic plantations of *Capparis decidua* (*kair*), supported by cottage-preservation units. Wild plantations of this species are already prevalent on such sites in the arid zone.

Special techniques

Protection against adverse weather. The storms cause mechanical damage to the fruits and branches, and lead to excessive transpirational loss of water resulting in water stress and desiccation. Owing to the sticky nature at ripening, the fruits, e.g., dates are spoiled by sand particles from the storms. Cold winds also cause damage. The planting of wind-breaks and shelter-belts is, therefore, absolutely necessary. For a wind break of a large area, the double-row planting of the trees of *Acacia tortilis*, with an internal row of *Cordia myxa* is recommended. For the protection of internal blocks of fruit-trees, a single row of closely planted trees of either *Acacia nilotica* var. *cupressiformis* or *Cordia myxa* around the blocks of 1-2 ha is beneficial.

Protection against intense radiation can be secured by selecting plant types with a suitable canopy architecture (e.g., Kinnow mandarin bearing fruits shaded by its well-formed dense foliage), close spacing, etc.

Moisture conservation. The arid-zone soils are poor in moisture-storage capacity and dry out quickly. Moisture conservation through careful management is, therefore, essential for achieving success. The structureless character of the surface soil, which often acts as a mulch, offers a unique opportunity to achieve this object. The surface of the soil, therefore, must be kept weed-free. Methods of sub-surface irrigation to supply water to the root-zones with a view to avoiding losses of moisture through evaporation and gravitation is more profitable.

Rainfed fruit production. For rainfed fruit production the accumulation of, run-off water can be secured to make up the deficit of water requirement. Fortunately, in the arid regions, even in light soils with high infiltration rate, there is a possibility of concentrating runoff to the extent of 10 to 40%, depending on the extent and pattern of rainfall (Ramakrishna and Singh, 1974), which can be much more in the case of slopy lands, hills and rocky areas (Abichandani and Yadav, 1974). A rational management of the catchment can further increase the run-off yield (Evenari *et al.*, 1971).

The runoff can be used for growing trees in such a way that each tree has its own micro-catchment area. The layout of the micro-catchment in relation to the location of the tree would depend upon the topography of the area. On hill slopes, or at the foothills, the fruit-tree will obviously be planted at the lower end of the catchment. Researchers in Israel have tried a square basin, shaped like a flat truncated pyramid at the lowest point in the micro-catchment for planting fruit-trees. The fruit-trees were planted on 125–1,000 m^2 catchments. In the plains, however, the catchment area may either be all around the tree or on two sides of it.

For determining the size of the micro-catchment for a tree species, various factors will have to be kept in view. Every fruit-tree has a water requirement for its optimum production. This requirement must be met from the local precipitation and from the runoff from the micro-catchment. It also has its own characteristics of root depth and spread. These factors determine the volume of the soil profile as a source for water-supply to the roots. The runoff water should be concentrated for storage in this soil profile. This would also mean that the runoff from the micro-catchment at one incidence of recharge should not ordinarily exceed the moisture-storage capacity. Considering the rainfall and catchment characteristics, in addition to the above factors, the size of the micro-catchment for a fruit-tree can be worked out (Mann and Pareek, 1974). Experimental evidence for suggesting a precise plant population per unit area in a particular system of runoff concentration (micro-catchment geometry) and the most efficient model of runoff generation and utilization is, however, required.

A good number of varieties of fig, almond, plum, olive, pomegranate, pistachio, peach, apricot, grapevine, sour and sweet cherries and apple have been grown in micro-catchments in Avdat and Shivta highlands under the rainfall pattern of Israel (Evenari *et al.*, 1971). At Avdat, peaches, apricots, almonds and loganberries were most successful, whereas at Shivta, fig, grapevine, pomegranate, olive and carob succeeded best. In the desert plains of India at the Central Arid-Zone Research Institute, Jodhpur, *ber* (*Z. mauritiana*) has been grown under various combinations of catchment size and slope, where the catchment is provided on both sides of the tree row. The data on the survival and growth have indicated that a combination of 54 m^2 catchment area per tree with 5% slope has given the best results one year after the plantation.

Fruits of the arid zone

Ber (*Zizyphus mauritiana*). It is the most drought-hardy fruit tree. *Z. nummularia* (*jharberi*) is found growing wild in the Indian desert and is an important source of leaf fodder and fuel. The small, round fruits have very little edible portion. *Z. rotundifolia* (*bordi*) is found wild under conditions of somewhat better rainfall, which produce round and slightly larger fruits than those of *Z. nummularia*. But the fruits still have very little pulp as compared with the large stone. The tree, however, is vigorous and upright unlike the slow-growing and spreading tree of *Z. nummularia*. Its wood is quite strong and is of a marginal timber value. The fruits are eaten fresh as well as after drying. A *ber* (*Z. mauritiana*) cultivar, *tikadi*, is popular in certain locations of the Thar desert. Its fruits are oblong, small, weighing 6-8 g each, and have lower pulp content than its stone. The fruits in green or yellow stage are acrid and become edible only when they turn red. The pulp at this stage has about 28° Brix total soluble solids (T.S.S.). Among the improved *ber* cultivars introduced from other regions of the country, the early-maturing cultivars have proved to be the best because of their bearing synchronising with the period of maximum availability of natural moisture. The cultivars, e.g., Gola, Seb, and Mundia, have proved better in these regions, although the commercial *ber* cultivars of the Punjab and Haryana States are Umran, Kaithli, Sanaur No. 2, Sanaur No. 5 and Thornless; of U.P. are Banarasi Karaka, Narma, Banarasi Pewandi, Aliganj, Jogia and Mundia; and of Rajasthan are Katha and Chomu. Five-year-old trees of Gola, Mundia and Seb have yielded 50-60 kg of fruit under rainfed conditions, with T.S.S. of 15-18° Brix. When irrigated, the yields of 80 to 140 kg per tree have been recorded in the case of Gola and Mundia cultivars (Table 1).

At Jodhpur, the flowering in the case of *ber* occurs during August and the fruit starts maturing from the first week of January, i.e. earlier than in other parts of the country.

Fruitfly (*Carpomyia vesuviana*) is a serious problem in *ber* cultivation. A preventive spray schedule incorporating three sprays of 0.02 per cent Parathion at three-week intervals starting from the fruit-set can, however, completely control the pest.

Date-palm (*Phoenix dactylifera*). The date-palm cultivation in the Thar Desert has considerable promise as compared with other regions of India because of the sufficient amount of heat-unit accumulation (Table 2) even by the end of June (before the monsoon sets in) and the high vapour-pressure deficit (<25 mb) prevalent in this region during the period of fruit development. These climatic characteristics cause faster maturity and result in avoiding fruit spoilage owing to checking and splitting. Date-palm production in the Thar Desert is, however, possible under irrigated conditions. Fortunately, the underground water reserves are abundant in this tract.

The results on the performance parameters of date-palm under arid conditions indicated that the spathe-opening, *doka*

Table 1. Fruit yield per tree under rainfed and irrigated conditions in the case of some *ber* cultivars

Cultivar	Rainfed		Under irrigation	
	Age (yr)	Yield (kg)	Age (yr)	Yield (kg)
Gola	6	45–50	5	85–110
Mundia	7	55–60	5	80–140
Seb	5	50–55	3	30–45
Jogia	7	45	5	60–80

Table 2. Heat-unit accumulation (above 50°F) at six arid-zone locations

Location	March	March-April	March-May	March-June	March-July
Jodhpur	1,155	2,314	3,710	4,995	6,196
Bikaner	1,082	2,192	3,664	5,041	6,365
Sriganganagar	992	2,080	3,558	4,901	6,255
Barmer	856	2,029	3,417	4,692	5,885
Jaisalmer	825	1,884	3,207	4,524	5,758
Bhuj (Kutch)	921	2,059	3,287	4,443	5,510

Table 3. Maturity and yield characteristics of some date-palm cultivars in the Thar Desert (7-year-old trees)

Cultivar	Maturity stage		Yield of doka fruits (kg)	Pulp (doka) %	T.S.S. (°Brix) Doka	Dang
	Doka	Dang				
Shamran	July 1	July 18	57·1	76·3	24	63
Hillawy	June 25	July 7	22·9	88·1	32	67
Khadrawy	June 27	July 10	3 8	88·8	36	—

formation and dang-formation were completed during the 3rd to 4th week of March, the 4th week of June to the 1st week of July and the 1st to 3rd week of July respectively (Table 3).

Sucker-production by the date cultivars started four years after plantation. The evaluation of the relative performance of the date-palm cultivars revealed that Shamran was the best variety in respect of growth (Table 4) and fruit yield, whereas Hillawy produced the best-quality fruits (Table 3). Under Jodhpur conditions, the fruits must be harvested at the *doka* stage either for the preparation of dry dates (*chhohara*) or for sale as fresh fruit; if it is a high-rainfall year like 1973 or 1975. If it is a dry year, the fruits may also be harvested at the late *dang* stage for the soft-date (*pind khajur*) preparation. The ripening of the dates on the trees may not be possible under the prevalent rainfall conditions.

Pomegranate (*Punica granatum*). It is another drought- and salt-tolerant fruit-tree. The variety Mrig bahar (flowering in July and maturing its fruit during October–December) is generally grown. The cultivars Mandor (Jodhpur), Saharanpuri and Seedless have been tried (Table 5), of which the first cultivar is commonly grown. The orchards are generally under irrigated conditions.

Fruit-cracking is a serious problem. The fluctuating conditions of soil moisture and atmospheric vapour-pressure deficit, along with the dry and hard nature of the peel, seem to be the prominent causes of fruit-cracking.

Guava (*Psidium guajava*). Although frost susceptible, is very drought-hardy. The orchard is seldom watered after harvesting the fruit in places where water is scarce till the advent of the monsoon rains. At Jodhpur, the fruits ripen by the end of December. Varieties, Allahabad Safeda and Lucknow-49 have given the best performance with regard to the yield and the quality of fruits in the arid zone.

Sweet orange (*Citrus sinensis*). The finest quality of Blood Red malta fruits are produced under the climatic conditions of Sriganganagar. Recently, Kinnow mandarin is becoming more popular, as

Table 4. Growth characteristics of some date-palm cultivars (7-year-old trees)

Cultivar	Crown height (cm)	The number of suckers per palm-tree			
		1972	1973	1975	Total
Shamran	115	0·5	5·2	0·7	6 4
Hillawy	95	—	6·0	6·0	12·0
Khadrawy	59	1·6	7 4	—	9 0
Medjool	46	3·0	1·7	0·7	5·4

Table 5. Fruiting characteristics of some pomegranate cultivars

Cultivars	Yield of fruits per tree	Fruit size (g)	T.S.S.	Acidity %
Mandor	100–250	150	13–16	0·3
Saharanpuri	150–300	180	16–18	0·56
Seedless	150–250	130	16	0·3

it is more adaptable to arid conditions. Out of the four varieties of sweet orange, namely Musambi, Jaffa, Navalencia and Valencia Late, tried at the CAZRI, Musambi gave the best results with regard to yield (100 fruits per tree) and quality (26% juice) of fruits. Musambi-trees have, however, started declining ten years after planting. The causes are being investigated.

Sour lime (*Citrus aurantifolia*). At Jodhpur, sour lime (Kagzi) has given excellent performance. The yield per tree is about 100 kg, with the juice percentage being 30 to 35. Decline in the trees of sour lime has started 10 to 15 years after planting.

At one of the substations of the CAZRI, Samdari, in the Barmer District, Kagzi lime, grapefruit and Pineapple malta have given satisfactory performance.

Grape (*Vitis vinifera*). Grape requires dry weather during flowering and fruiting. Rain or humid weather at the time of ripening causes the splitting of berries and induces fungus diseases. In the arid zone, the berries ripen well before the onset of the monsoon. At Jodhpur, the berries of Beauty Seedless mature in the last week of May and those of Thompson Seedless in the first week of June.

A large number of varieties of grape were tried at Jodhpur. Out of them, Beauty Seedless has been found to be the hardiest. Although Thompson Seedless has given the best-quality fruits, yet it has declined after giving a couple of good crops. Vineyards of other varieties, e.g. Anab-e-Shahi, Selection-7, Kandhari and Black Prince, though adjudged hardier than Thompson Seedless, have also declined 6–7 years after planting. An analysis of the reasons of this decline in fruit production after an initial good performance has revealed a causal relationships with (1) pests, such as thrips and nematodes, (2) diseases, such as anthracnose and powdery mildew, (3) deficiencies of nitrogen, zinc and manganese and (4) faults in relation to training and pruning.

Papaya (*Carica papaya*). Viral and fungal diseases which limit papaya cultivation in the humid regions of the country are of a little occurrence in the arid zone. The papaya fruit develops an excellent flavour under the dry and hot conditions of this region. Many people do not relish the undesirable odour which develops in the fruits grown under the climatic conditions of other regions. Papaya-growing is, therefore, becoming popular in these dry regions, wherever irrigation is available.

The commonly grown variety is Honey Dew which gives 30 to 50 kg of fruit per plant, with a T.S.S. of 12–13° Brix. Other varieties, namely Washington, Barwani Yellow, Co. 1 and Coorg Honey, are new introductions into this region. The variety Washington has yielded 40 to 60 kg of fruit per plant.

Lasoda or gonda (*Cordia myxa*). It is a drought-tolerant tree which hardly needs any irrigation after one year's growth. Flowering takes place in February and the fruits mature for harvesting in April-May. The small roundish green fruits are borne in clusters, and have a slimy and acrid pulp around a hard stone. The fruits are harvested in the green stage and are used for making pickle. The yield per tree is about 100 to 200 kg. Ripe fruits are orange yellow when the pulp becomes more slimy and sweet. The leaves are large and coarse and are used for covering the fruits of pomegranate to protect them against birds, squirrels and dry weather.

The other fruits which have performed well are mulberry, *phalsa* (*Grewia subinequalis*), custard-apple and bael (*Aegle marmelos*).

Arid regions, with their irrigated sites, in particular, are, therefore, the potential foci for meeting the increasing demand of fruits. Fruit-growing assumes greater importance in view of the need to fight against malnutrition prevalent in the underdeveloped regions of the country.

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DESERT RODENTS AND THEIR MANAGEMENT

ISHWAR PRAKASH

ANIMALS, domesticated as well as wild, are known to play an important role in altering the natural conditions in various environments. Since the deserts are perpetually threatened scarcity zones, their impact on the land and resources is more apparent. The rodents not only deplete the vegetation resources, but also sometimes alter their composition because of over-utilization from productive to less productive and unpalatable species. The numbers of rodents fluctuate considerably, seasonally as well as from year to year. Depending upon their density in the desert, they have been observed to be serious agents of soil erosion, as they excavate a good deal of soil from their burrows every now and then. The compact soil, thus loosened, is kept piled up near the burrow openings and is carried away by the strong desert winds. To the crop fields, the rodents are dangerous only next to locust. Grasslands in the arid and semi-arid regions of India are so much affected by the presence of a variety of rodent species that no serious animal production can be achieved without their management. Thus the rodents are a potent factor responsible for accentuating desertification.

Table 1. Percentage distribution of rodents in various habitats in the desert biome of Rajasthan (after Prakash *et al.*, 1971)

Rodent species	Sandy	Gravelly	Rocky	Ruderal
F. pennanti	14·2	—	35·8	50·0
G. n. indus	100·0	—	—	—
G. gleadowi	56 0	—	—	44 0
T. i. indica	28 8	10 0	3 6	57·6
M. hurrianae	60 0	17·0	—	23 0
R. c. cutchicus	—	—	100·0	—
R. meltada pallidior	37·0	1·6	5 1	56·0
R. gleadowi	66 6	33 3	—	—
M. musculus	—	—	—	100·0
N. b. booduga	—	—	—	100·0
M. cervicolor ssp.	—	—	100 0	—
M. c. phillipsi	—	—	100·0	—
M.p. sadhu	28 0	13 3	53·3	13·3
G. e. gujerati	25 0	12 5	—	62·5

Thus communication deals with the salient features of the biology of rodents of the Indian arid zone (Punjab, Haryana, Rajasthan and Gujarat) and their management to an economically effective level.

DESERT RODENTS

Habitat diversity and rodent associations

Eighteen species of rodents occur in the desert zone. Several of them are widely distributed in the Rajasthan desert, whereas some are restricted to a particular habitat. Among the widely distributed rodent species are *Funambulus pennanti*, *Tatera indica*, *Meriones hurrianae*, *Rattus meltada pallidior*, *Mus platythrix sadhu* and *Golunda elliotі gujerati*. These are found in more than two habitat types (Table 1).

The Indian Gerbil, *Tatera indica indica* and *Rattus meltada pallidior* are associated in the crop fields on the outskirts of villages. In the northernmost district of the desert, the mole rat, *Nesokia indica*, is also found with them. In the south-eastern desert, *Tatera-R. meltada* association is joined by *Golunda e. gujerati.*

In the irrigated fields in the Punjab and Haryana States, *Rattus meltada* and *Mus* spp. are most predominant. *Bandicota bengalensis*, *Tatera indica* and *Nesokia indica* are also common. In Gujarat, however, the species composition of rodents is more or less like that in the Rajasthan desert.

Relative abundance in relation to edaphic factors

With regard to the ecological distribution of rodents, three major soil types have been recognized, viz. dune soils, desert soils, and red and yellow soils in the desert (Prakash *et al.*, 1971). The first type of soils generally occur in the Barmer, Jaisalmer, Bikaner, Churu and Jhunjhunu districts. *Gerbillus gleadowi* is the commonest rodent found in the dune soils (Prakash and Rana, 1973). Desert soils are usually found in the inter-dunal regions and in the sandy plains. These soils are spread all over the desert region, where *M. hurrianae* and *Tatera indica* are commonest, particularly in parts of the Pali, Jodhpur, Nagaur and Bikaner districts. The red and yellow soils are found along the foothills of the Aravalli ranges and are mainly represented in the southern parts of the Pali, Sirohi, and Jalore districts. *Golunda ellioti gujerati*, *Mus platythrix sadhu* and *Rattus meltada pallidior* are more commonly found in such types of soils. To some extent, *R. m. pallidior* and *Mus b. booduga* are associated with the soils which are irrigated from wells, and *Nesokia indica indica* with soils irrigated with groundwater (in the Sriganganagar district). In saline soils, *Meriones hurrianae* and *Tatera indica* are common.

During a quantitative study of the density of the Indian desert gerbil, *Meriones hurrianae* (Prakash *et al.*, 1971), it was revealed that their average annual number tended to be low, where the clay percentage in the soil was relatively high and the soil had a higher permeability for the seepage of water (Table 2). About 40 years ago, when there were no canals in the Sriganganagar district and the country had rolling sand-dunes, the predominant rodent fauna consisted of *Gerbillus gleadowi* and *Meriones hurrianae.* With the coming of the Ganga Canal, the soil texture of the region changed and it became more clayey and *Meriones hurrianae* has since been replaced by *Nesokia indica indica*, which, it is speculated, mirgrated into the district along with the canal system and has now finally established itself in the canal-irrigated crop fields.

Table 2. Density of *Meriones hurrianae* in different bioclimatic zones of the Indian desert

	Jaisalmer-Chandan tract	Palsana-Lachh-mangarh tract	Barmer-Gadra Road tract
Average annual number of *M. hurrianae* per 90 × 90 m plot	31	247	458
Percentage of clay in the soil	5.3	4.5	3.1
Permeability g/hr	0·8081	0·3485	0·1622

Population fluctuations

The seasonal variations in the numbers of various species of rodents of the Rajasthan desert have been studied in some detail (Prakash, 1975 a,b). Among the field rodents, the peaks in density differ from season to season. On an overall basis, the density of most species is lowest during the summer months and tends to increase after the rainy season.

Behaviour patterns

Locomotion: Almost all the desert rodents are good climbers. Those belonging to *M. hurrianae* have been observed on *Capparis decidua* shrubs for feeding upon its ripe fruits, and on *Acacia tortilis*, *Pro-*

sopis cineraria and *Albizzia lebbek* for debarking them. *Rattus c. cutchicus*, a crevice-dweller, feeds on the flowers of *Euphorbia caducifolia*, a thorny shrub, 2 to 4 metres tall. The flowers are usually lodged on the apical portions of the shrub. The palm squirrel, *Funambulus pennanti*, is arboreal. *Rattus rattus* and *Mus musculus*, usually found commensal with man, are also excellent climbers.

Activity pattern : Quantitative studies on the activity pattern of most of the rodents are wanting. The psammophile gerbils, *Gerbillus* species, venture out of their burrows at dusk during summer and continue to be active throughout the night and cease their outside activity before dawn.

The crevice-dweller and nocturnal *Rattus c. cutchicus* also, probably, behaves like *Tatera indica indica*, some quantitative data about the activity pattern of which are available with us. In a particular street in the Bikaner Town, the Indian gerbils were counted during summer and winter at every hour at night. During summer, the gerbils ventured out late at about 22 hours and the peak numbers were seen at 23 hours and the activity gradually declined till 05 hours. During winter, however, the peak activity reached early during the night and started declining quickly after 2400 hours, presumably a behavioural shift to shun very cold nights.

The diurnal rodents are also not active throughout the day. The palm squirrel, during summer, climbs up the trees and passes the hottest period in a state of inactivity. It is active during the morning and during the late evening when it is cool. A similar behaviour is observed in the case of the desert gerbils, *Meriones hurrianae*, which were observed in a quadrat during summer and winter. The desert gerbils move out of their burrows early in the morning and cease their activity by 11 a.m. During this period also, they visit their burrows frequently and are not out for a long time. They venture out again in the evening and many of them can be seen up to 6-7 p.m. whereas during winter they remain outside almost throughout the day, beginning their activity late in the morning and ceasing it early in the evening (Prakash, 1962). This shifting activity pattern in rodents is probably an indication of adaptation to withstand extremes of desert temperature.

Territoriality: None of the rodents found in the Indian desert is territorial in the strict sense. The individual home ranges of all the rodents studied overlap one another, clearly suggesting that they do not defend their entire ranges. Field observations indicate, however, that the palm squirrels show territorial behaviour when they are on the branches of the trees or near the crevices where they take shelter in their nests. At feeding time, as many as 15 squirrels have, however, been observed in a small space of about 5 m^2. During the mating season as well, 4-5 male suitors chase and surround a single female. No sooner is one of them accepted than the others wait for their turn, as the female palm squirrels are promiscuous in their mating habit and a female mates with 2-4 males during one oestrus.

In the case of *Meriones hurrianae*, almost a similar situation has been observed (Fitzwater and Prakash, 1969). Intra- and intersexual fights and chasing were observed quite often. After a few chases, however, they tolerate one another and spend most of the time in foraging. However, they are liable to resent too close an intrusion upon one another's vicinity and start throwing dirt at one another with their hind feet. This behavioural trait of throwing dirt* on other members of the species is perhaps indicative of territorial behaviour among gerbils. The gerbils start digging on sighting another member of the species too close, and it, usually, quickly retreats. This signal also indicates a sort of threat behaviour. It appears that desert gerbils adjust themselves to the presence of one another by maintaining a distance ranging from two to four metres. The defence of territory is

**Meriones* and *Tatera* throw dirt on the chasing snakes, hedgehogs and large spiders, probably as a means to divert these enemies.

initiated only when another member tries to cross these limits. They only protect the immediate vicinity of the burrow openings which they use more frequently.

The nocturnal gerbil, *Gerbillus nanus indus*, quite often lives in the burrows of the diurnal *M. hurrianae* over sandy plains. It seldom stays with *T. indica* which is more aggressive species and is also nocturnal. Their interrelationship inside the burrows is not known. In the laboratory cages, *M. hurrianae* and *G.n. indus*, when maintained together, seldom fight, but *T. indica indica* gives them a hard time and usually kills them.

Communication, visual: The eyes of *T. indica indica* are larger than those of other desert rodents, but its vision is not very good as was evidenced by our field observations made during nights in dim light. But the squirrel, *F. pennanti*, appears to have an excellent eyesight. Our knowledge of the visual aspects of nocturnal rodents is limited. However, observations in large cages indicate that all can see very well during the day. Therefore the visual communications should play an important role, at least for a short distance.

Auditory. The squirrel, *F. pennanti*, is very vocal and has several notes signifying different signals. Its alarm call is more often produced while defending the young in the nest. This squeak is usually accompanied with a jerk of the tail. No sooner does one squirrel emit these shrill calls than all the squirrels in the near vicinity join the chorus. *Tatera indica*, *Meriones hurrianae* also squeak when they are trapped. When they are handled, they sometimes emit a long shrill call, but it is not so loud as that of the squirrel. *Rattus rattus* also squeaks when handled, but whether it is meant for communicating the danger to others or it is a distress call is not definitely known.

Drumming: The desert gerbil, *M. hurrianae*, thumps on the sand, under several situations, almost invariably signifying danger and it is, thus, regarded as an alarm signal. The thumping noise or drumming is produced repeatedly and with great speed by striking one of the hind feet on the ground. No sooner do the wing beats of predatory birds make the colony 'duck' inside the burrows, than the desert gerbils perform drumming from inside the burrows. This drumming is not produced while a gerbil is chased by another of the same species. During mating also, thumping is done by the male, presumably to warn other gerbils in the surrounding area. This thumping lasts for 0.3 second, on an average.

There are evidences to suggest that the auditory faculty in this desert rodent is much more efficient than the visual one. Contrary to the conjecture that their preception of sound travelling through the solid soil medium is stronger, we also observed (Fitzwater and Prakash, 1969) that the noise of the wing-beats of the predatory birds, pariah kites (*Milvus migrans*), *shikra* (*Astur badius*), tawny eagle (*Aqila rapax*) and the house crow (*Corvus splendens*) are quickly preceived by the merion gerbil. Interestingly, however, the sound of the wing-beats of babblers (*Turdoides* spp.), which are not predatory, never disturb them. It may indicate that the desert gerbils can possibly differentiate between the wing-beat noises of harmless and predatory birds. This specialized differentiation may be achieved owing to the hypertrophised tympanic bullae. The length of the tympanic bulla of *M. hurrianae* is 35.4% of the condylobassal length of the skull and this condition indicates that their typanic bullae are enlarged (as compared with those of rodent species inhabiting humid climate) and probably help the gerbils to detect and differentiate various types of sounds. It has also been suggested that this hypertrophy of the tympanic bullae helps to resonate and amplify the sound for enhancing preception. The hypertrophy of the tympanic bullae is regarded to be an adaptation to the increased perceptibility of the mating call and the sounds of movements of snakes and predatory birds.

On the basis of these ecological and ethological studies, we have based all our strategies of control operations. Most of these strategies have been incorporated into the National Programme for Rodent Pest Management.

LOSSES INFLICTED BY RODENTS

Owing to scanty rainfall and other climatic adversities in the arid zone, crop production and the survival of a substantial vegetative cover are rather difficult. The unduly dense population of field rodents in the Indian desert further lowers the possibilities of enhancing the productivity of the arid-lands.

The natural desert vegetation has gradually changed from highly palatable and nutritious perennial grasses to inedible annual weeds because of rodent depredations assisted by the process of overgrazing by livestock (Prakash, 1976). The losses caused by rodents to grasses have been extensively studied and it has been found that unless the rodents are controlled, the chances of range improvement are only feeble. To standing crops also—both *kharif* and *rabi*—damages are substantial. The attack of rodents on the *bajra* crop in western Rajasthan during 1973 and on groundnut in Saurashtra during 1976 was severe. Rodents, *Tatera indica* and *Rattus meltada*, damage the gram, wheat and *sarson* crops also. They damage irrigation channels, dams, soil-conservation furrows and are potential agents of soil erosion (Fitzwater and Prakash, 1973; Barnett and Prakash, 1975; Prakash and Ghosh, 1975; Prakash, 1976).

THE CONTROL STRATEGY

A large number of toxicants and anticoagulants have been evaluated by us at the CAZRI for assessing their efficacy in the control of the predominant rodent species, occurring in the Indian desert and extensive experiments have been carried out to find suitable baits for them. On the basis of such results, the control strategy has been outlined as follows.

Crop fields and threshing-yards : As far as possible, rodent-control operations should be taken up before the sowing of crops. The active burrows are to be surveyed and pre-baiting (cereal-flour of cracked grains 97 parts and vegetable oil 3 parts in the form of 1g balls or lumps, 6 g per active burrow opening) done on the first and third day. On the fifth day, 2% zinc phosphide is added and the baits are distributed. This operation will take care of 70 to 80% of the population of the field rodents. The residual population cannot be tackled by poisoning with zinc phosphide, as most of the rodent species develop poison and bait shyness after a single exposure to this toxic chemical. The residual population should be controlled by fumigating the burrows. On the sixth or seventh day, all burrow openings are closed. On the eighth day in reopened burrows, tablets of aluminium phosphide are put at the rate of 1.5 g per active burrow opening. This operation will control the residual population of the rodents and must be taken up at the beginning of the *kharif* and *rabi* seasons.

Residential premises and godowns: On the first day, the volunteers should collect 1 kg of food material representing the bait requirement from each household for fields as well as for houses. They should visit individual houses in a village and predetermine the places where baits are to be placed. An assessment of the total and daily requirements of the bait, the poison and the manpower required should also be made. To prepare the bait material, the collected cereals will be crushed and 5% master mix (0.5%) concentrate of an anticoagulant (Warfarin) will be mixed and kept ready for distribution. On the second day, the bait will be placed in suitable containers, such as broken pitchers, mud channels, coconut shells and bamboos. In each house, the bait will be placed at 2–4 points with about 300 g of it per house and the baiting should continue for three weeks. The dead rats should be collected and buried. This operation must be repeated once in six months to keep the village comparatively rodent-free.

This method will bring down the population of the house rat, *Rattus rattus*, to a very low level, but some house mice, *Mus musculus*, will survive and to control which, regular trapping should be carried out by the villagers. Various principles of rodent control have been discussed in detail elsewhere (Barnett and Prakash, 1975; Prakash, 1976).

SUMMARY

Rodents are a serious pest all over the country and especially in the desert biome. Their preponderance, relationship with habitats and edaphic factors, population fluctuations and behaviour in the Indian desert have been discussed. The losses caused by them to the crop fields, threshing-yards, residential premises and stored foodgrains have been outlined. Proven control strategies have been described.

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INSECT PESTS AND THEIR CONTROL

K. S. KUSHWAHA AND S. K. PAL

FARMERS in the arid zone need to adopt an ecodevelopment-orientated programme of animal and crop production under conditions of natural rainfall, not exceeding 300-400 mm annually, as the major source of water. During a few showers in the arid zone of Rajasthan, which forms a part of the great Indian desert, the people gamble with agriculture by throwing seeds of *bajra* on the sand-dunes, hoping to harvest the crop after the rains. Occasionally, they get a good crop, but failure is the normal rule.

Ninety-three per cent of the area under coarse grains (20–25 % of the total foodgrains) and 91 per cent of the area under pulses (9–11% of the total food production) is dependent upon rainfall. The coarse grains and pulses together cover about 50 per cent of the total area under foodgrains, but they account for merely 33 per cent of the total production. As such, production and protection research on coarse grains and pulses must be intensified.

PROBLEMS AND PROSPECTS

To highlight the vagaries of pestilence under the cropping pattern of the arid and semi-arid zones, the major pests infesting the traditional and some new crop introductions to supplement the deficiency in terms of remunerative returns are discussed in this paper.

GENERAL PESTS

Coarse grains. Generally, the sporadic epidemics of different pests, except the tissue-borers which have become endemic, the major pests of the region have been listed along with their chemical control, based on an easy access of the cultivator to the commercial insecticidal products (Table 1). In the case of *bajra*, the type of damage and the incidence of pests have been categorized as (i) leaf damage due to grasshoppers, caterpillars and beetles, (ii) the presence of deadhearts, (iii) the incidence of the shoot bug, *Perigrinus maidis* Ash., and the earhead caterpillar, *Eublemma silicula* Swinhoe, to assess the extent of damage caused by the population in each case. Since 1968, the incidence of *Pyrilla perpusilla* Walk. has unusually been recorded in the case of *bajra, jowar* and maize. Searching for the sources of resistance in the germplasms is an important current approach in breeding crop varieties, but the factor complicating this problem in the unirrigated areas is that the insect fauna tends towards polyphagy (Pradhan and Pant, 1970). However, the screening of *bajra* varieties for resistance to white grub at Tabiji Farm (Rajasthan) indicated the possibility of getting certain lines which may show some type of resistance in the world germplasm of *bajra* to this pest.

In the case of sorghum, the germplasms have been studied for resistance to three major pests, viz. the sorghum stem-borer, *Chilo partellus* (Swinhoe), the shootfly, *Atherigona varia soccata* Rond. and the sorghum midge, *Contarinia sorghicola* Coq. (Anonymous, 1971).

The timely use of insecticides can reduce

Table 1. Insect pests of *bajra*, sorghum and maize

Pest species (family) according to sequence of incidence	Control measures
Termites (Termitidae): *Odontotermes obesus* Ramb.; *Microtermes anandi* Holmg.	Aldrin or heptachlor (5%) or BHC (10%) dust @ 25 kg/ha to be incorporated into soil about 15 cm deep
White grub (Melolanthinae): *Holotrichia consanguinea* Bl.; *H. serrta* Fabr.; *H. insularis* Brenske *Anomala bengalensis* Bl.	Phorate (10 G) or thiodemeton(5%) or lindane (6%)@ 20 kg/ha mixed with the soil. (For controlling beetles, use mechanical-cum-chemical method, vide text)
Sorghum shootfly (Anthomyidae): *Atherigona varia soccata* Rond. ; *Bajra* shootfly, *A. approximata* Malloch.	Seed treatment with carbofuran (50 WP) @ 60–100 g/kg (or a pre-sowing soil application of phorate or thiodemeton granules @ 20 kg/ha, 40 kg/ha respectively)
Grasshoppers (Acridiidae): *Chrotogonus trachypterus* Bl.; *Hieroglyphus nigrorepletus* Bol.; *Oxya ebneri* Will.	BHC (5%) dust @ 25 kg/ha
Shoot-borers: *Chilo partellus* (Swinh) (Pyralidae); *Sesamia inferens* (Walk.) (Noctuidae).	Endosulfan (4 G) or carbaryl (4 G) or lindane (2 G) or quinalphos, (5 G) three times @ 5 0, 7·5 and 10 0 kg/ha, after 20, 30 and 40 days of germination
Hairy caterpillars (Arctiidae): *Amsacta moorei* Butl.; *A. albistriga* Walk.; *A. lineola* Fabr.	Endosulfan (4%) or carbaryl (5%) dust @ 15–20 kg/ha
Armyworm (Noctuidae): *Mythimna separata* Walk.; Grey weevil (Curculionidae).: *Myllocerus maculosus* Desb.	BHC (5%) or carbaryl (5%) dust @ 20–25 kg/ha or carbaryl 0 1% or endosulfan 0·075% spray
Aphid (Aphididae): *Rhopalosiphum maidis* Fitch.	Phosphamidon or dimethoate 0·03% or methyl demeton 0 025% spray
Sorghum midge (Cecidomyiidae): *Contarinia sorghicola* Coq.; Earhead bug (Miridae) *Calocoris angustatus* Leth.	Endosulfan 0 05% or carbaryl 0·1% or lindane 0·1% or malathion 0·03% spray (or endosulfan 4% or carbaryl 10% dust @ 12 kg/ha) after 90 per cent earhead emergence; repeat 4–5 days after the first application

the loss to the extent of 54.91, 50.26 and 61.15 per cent on account of *A. soccata*, *C. partellus* and *C. sorghicola* respectively. But while working out the cost-benefit ratio, the cost of control measures would involve an outlay of Rs 370 to 440 per hectare, depending on two or three applications of carbofuran and endosulfan. This high cost of insecticides, added to the cost of application on account of labour, besides the cost of cultivation, is evidently beyond the means of an average cultivator. The circumstances, considering the spending capacity of the cultivator, make it incumbent upon researchers to explore cheaper methods of avoiding the depredations of these pests. Consequently, the alternative methods of pest management have been investigated, involving a more judicious use of insecticides to supplement the cultural methods.

The shoot-fly remains active throughout the year, but has low threshold activity during the first week of July, as evinced by the low percentage of deadhearts. In case, therefore, this period is adhered to as a normal time of sowing, the infestation is avoided to a considerable degree. On the other hand, the delayed sowing increases it to a great extent. The early sowing ensures the protection of the crop against shoot-fly without any chemical control. Additionally, the infestation of the crop with the midge, which appears by the end of September, is also avoided because the grains mature and, consequently, no injury can be expected in such an early crop. In sequence of the integrated approach, the insecticidal control is needed for the stem-borer alone. As such, the two or three applications of endosulfan (granules) would achieve the control of the borer effectively at a mere cost of Rs 87 to 156 per hectare instead of Rs 370 to 440.

In the case of maize, the germplasms, have been screened for resistance to the borer, *C. partellus* (Mathur and Jain, 1972). Besides the adjustment of the date of sowing, the disposal of stubble after harvesting the crop is an important practice worth adopting. The ploughing down of stubble reduces the borer attack substantially. The larvae hibernating in the stubble are a source of infestation for the next crop and should be destroyed *in situ*. Hence cultural operations, viz. the early and timely sowing and the ploughing down of stubble make it possible to avoid the shoot-fly and midge infestations without entailing high costs to control them.

Pulses. Pulses, as a group, are more drought-resistant than cereals and, hence, have found a niche in the cropping pattern characterized by moisture stress. Of these, gram is the major crop in terms of hectares and production. Timing the use of insecticidal measures, particularly against the pod borer, *Helicoverpa armigera* (Hubn.), just when the first pods have been formed is most important, but the treatment may have to be repeated after three weeks. It may be mentioned that the whitefly, *Bemisia tabaci* Genn., transmits the yellow mosaic of green gram (*mung*, *Phaseolus aureus* Roxb.) and *moth* (*P. aconitifolius* Jacq.) whereas the aphid, *Aphis craccivora* Koch., transmits the mosaic of cowpea (*Vigna sinensis* Savi.). The granular systemic insecticides applied to the seed furrows have proved quite effective. Table 2 shows the pesticides found useful against the common pests of pulse crops.

Oilseeds. A major contribution has been made to the knowledge of the pests of oilseed crops in India and their control (Rai, 1976). The major pests recorded on various crops cultivated in Rajasthan, together with the insecticides commonly recommended to control them, are presented in Table 3.

Forage crops and pasture. Significant advances have been made in the field of forage and pasture pests under an ICAR Project 'Investigations on Forage and Pasture Insect Pests of Rajasthan' (Kushwaha and Bhardwaj, 1977). Pests of the desert grasses have been studied by Pal (1975).

PESTS OF SPECIAL ECONOMIC IMPORTANCE

White grubs. The polyphagous white grub or leaf-chafer species, the major being *Holotrichia consanguinea* Blanchard (Scarabaeidae: Melolonthinae), has proved to be the deadliest pest threatening the entire crop production, nullifying the gains of high-yielding-variety programme in the arid and semi-arid zones. The crops worst affected by the underground grub infestation are *bajra*, groundnut, sorghum, maize, *kharif* pulses and chillies. The beetles crawl out of their subterranean

Table 2. Insect pests of pulses (green-gram, *moth*, gram, cowpea)

Pest species (family according to sequence of incidence)	Control measures
White grub and termite spp. Cutworms (Noctuidae) *Agrotis ipsilon* Hugnagel, *A. spinifera* Hubner Galerucid beetle (Galerucidae), *Madurasia obscurella* Jacoby	*Vide* Table 1 Aldrin or heptachlor 5% dust @ 25 kg/ha BHC 5% or carbaryl 5% dust @ 20–25 kg/ha
Green Jassid (Jassidae), *Amrasca kem* D.	*Vide* Table 3
Hairy caterpillars (Arctiidae), *Amsacta moorei* Butl., *Diacrisia obliqua* Walk.	*Vide* Table 1
Caterpillars (Noctuidae), *Plusia orichalcea* Fabr, *P. nigrisigna* Walk. *Anticarsia irrorata* Fabr. *Laphygma exigua* Hubn.	BHC 5%, carbaryl 5% dust @ 20–25 kg/ha

Table 3. Insect pests of oilseed crops

Pest species (family) according to sequence of incidence	Control measures
Mustard, *Brassica campestris* Mustard sawfly (Tenthredinida) *Athalia proxima* Klug.	Seed treatment with lindane and phorate @ 2·5 kg and 1·0 kg/100 kg of seed
Mustard aphid (Aphididae) *Lipaphis erysimi* (Kalt.)	Spray malathion 0·05%
Painted bug (Pentatomidae) *Bagrada cruciferarum* Kirk.	Phosphamidon 0·03%
Leaf-miner (Agromyzidae), *Phytomyza atricornis* Meigen.	Methyl demeton 0·03% Dimethoate 0·08%; Carbaryl 0·2%
Til, *Sesamum indicum*: Til caterpillar (Pyralidae) *Antigastra catalaunalis* (Dupon)	Carbaryl 0·1%
Til hawk moth (Sphingidae) *Acherontia styx* Westw.	BHC 5% dust
Castor, *Ricinus communis* Castor semilooper (Noctuidae), *Achaea janata* Linn.	Carbaryl 0·1%
Hairy caterpillar (Lymantriidae) *Euproctis lunata* Walk.	BHC 10% dust
Castor mite (Tetranychidae), *Tetranychus telarius* Linn.	Phosphamidon 0·03%
Castor capsule-borer (Pyralidae) *Dichocroces punctiferalis* Guen.	Malathion 0·1%
Groundnut (*Arachis hypogaea*) Termite *Odonototermes obesus*; White grup *Holotrichia consanguinea* *Amsacta moorei*	*Vide* Table 1
Safflower (*Carthamus tinctorius*) Safflower aphid (Aphididae) *Uroleucon* (*Uromelan*) *compositae* Theob.	Methyl demeton 0·03% Dimethoate 0·03%
Sunflower (*Helianthus annus* Aphid) (Aphididae) *Brachycaudus helichrysi* (Kalt.) *Aphis gossypii* Glov.	Vide Table 1
Jassids (Jassidae) *Distantasca terminalis* (Dist.) *Empoasca lybica* deG., *E. motti*, Pruthi, *Amrasca* sp.	Phosphamidon 0·03%
Whitefly (Aleurodidae) *Bemisia tabaci* Gen.	Dimethoate 0·03%

abodes immediately after the first pre-monsoon or monsoon shower, between 7.30 and 8.00 p.m. and congregate on their host plants in large numbers. This is the most vulnerable stage of the pest and the most appropriate time for adopting large-scale control operations.

A wide-ranging recommendations have been made on the chemical control of grubs and beetles under Rajasthan conditions (Kaul *et al*., 1966; Rai *et al*., 1969; Pal and Doval, 1970; Sharma and Shinde, 1970; Pal, 1972; Sachan and Pal, 1976). Phorate (10 G) at the rate of 1.0–1.5 kg a.i. per hectare is commonly recommended for application to the soil. Additionally, a strategy for adoption on community basis is to attack the adults while they are congregating for feeding during the night before their retreat to the soil by about 4.30 a.m. After feeding for sometime, they start mating when they become sluggish. Then, they can be jerked down from the trees in large numbers and killed by drowning them in kerosenized water. Their host plants can also be kept sprayed before the emergence of the insects, with 0.2% carbaryl (50 WP) or 0.05% monocrotophos (40 EC).

Termites. Investigations by Roonwal and co-workers have made a major contribution to the faunal composition and ecology of termites in the desert area, culminating in a monograph *Termite Fauna of Rajasthan, India* (Roonwal and Bose, 1964). Of the 32 termite species known from Rajasthan, 25 occur in the desert portion. Kushwaha (1972) studied the pest aspects of four species of termites in Rajasthan, and discussed their damage to fruit-trees and pastures. Termite management needs greater attention in view of their attack on pulses, cereals and forest-trees in the desert agro-ecosystem. However, their control under complex subterranean habitation is by no means easy. The common species infesting the various crops (Tables 1, 2 and 3) and the forest plantations of *shisham* (*Dalbergia latifolia*) were protected by the application of aldrin and heptachlor up to two years.

Grasshoppers and locusts. Pradhan and Peswani (1961) estimated that the 'phadka' grasshopper. *Hieroglyphus nigrorepletus* Bolivar, individually consumed on an average 42 grammes of green foliage of maize (*Zea mays* L.) during its lifetime, and thus the loss calculated was 18 per cent, presuming that during normal years at Delhi, the population in the maize fields goes up to 10 per square yard.

Roonwal's (1945, 1953) hypothesis for the prediction of swarming in the case of the desert locust, and discourses by Uvarov on new evolutionary effect are significant contributions to locust biology. Desert locust breed only in such areas at such times as may be characterized roughly by a temperature range of 20°–30°C and at the relative humidity range of 45–80 per cent. Bhanotar (1975) has reviewed locust activities in the arid and semi-arid regions of Rajasthan.

Cutworms. Cutworms (Noctuidae : Agrotinae) comprise the most notorious group of insect pests. They are polyphagous sporadic pests, which feed voraciously during dark hours. Most of the species have high preference for gram, potato and tobacco. Severe damage has been recorded during the *rabi* season, particularly in low-lying areas, flooded during the previous monsoon. Generally, *Agrotis ipsilon* Hufn. and *A. flammatra* Schif. commonly infest crops in the plains, whereas *Euxoa segetis* Schif., in addition to the above species, is a regular major pest in the hills. They crawl out of their subterranean abode at night and cut foliage or shoots to drag them into the soil. Gram in the seedling stage is nibbled close to ground and at a later stage, the upper succulent branches are cut, but the damage varies from variety to variety; more woody varieties are damaged less. Peculiarly, they destroy many more plants than they actually consume.

Four generations occur in the plains. It is speculated that they are regular migrants from the plains to the hills at the end of spring, and return to the plains at the end of autumn. But it is possible that certain species undergo aestivation or breeding in remote situations to a limited extent on some unknown weeds during this critical summer duration. Immature stages are susceptible to direct sun.

INSECTICIDE RESIDUES

The safe limits of malathion and carbaryl on lucerne and cowpea necessitated the determination of residues. Malathion reached the below-tolerance limits in 1-6 days on lucerne (Amin *et al.*, 1970), whereas carbaryl became dissipated below the tolerance limits in 3-5 days on cowpea (Srivastava and Sharma, 1976). The milk of cows fed on malathion-treated lucerne had no detectable residue (Amin *et al.*, 1970). The endosulfan-treated *ber* fruits at 0.1 per cent dosage showed no detectable residue after 20 days and were recommended fit for human consumption after two days, since the residues left were below the tolerance limit (Kushwaha and Pal, 1976).

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LIVESTOCK PRODUCTION—PROBLEMS AND PROSPECTS

R. M. ACHARYA, B. C. PATNAYAK AND L. D. AHUJA

LIVESTOCK-FARMING plays an important role in the economy of the arid region, as there are risks involved in crop-farming because of scanty and uncertain rainfall. It provides a very sizeable proportion of the population of the region with employment. A socio-economic survey conducted by the Central Arid-Zone Research Institute (CAZRI), Jodhpur, indicates that about two-thirds of the earning members in the households surveyed in this region followed animal husbandry as their main occupation (CAZRI, 1965). The livestock sector in Rajasthan accounts for 12% of the total income of the State (Planning Commission, 1973) and considering that this sector provides two-thirds of the population in the arid areas with employment, the contribution of livestock to the economy of this region would even be much higher. In addition to managing livestock, a sizeable population in the region is engaged in the handicraft industry, utilizing animal products, such as wool, skins, hides, hair, and in marketing milk, milk products and livestock. The arid region contributes almost 40% of the total wool produced in the country. Similarly, the contribution of this region to the production of meat, milk and other animal products in the country is quite substantial.

Cattle, sheep, goats and camel are the important livestock species contributing to the economy of the region. Studies on the comparative economics of sheep and goats under range-management conditions indicate that goats are 40 to 160% more economical than sheep (Abidi, 1970; Wahid, 1975). Knoss (1969), on the basis of his work done at Hissar, has also indicated that goats are more economical than sheep and the two species do not compete with each other in utilizing the naturally available vegetation resources. Theoretical considerations on the relative economics of the rearing of cattle, sheep and goats in the arid region of Rajasthan, while primarily maintained on free-range grazing or browsing, with some supplementary feeding to cattle during lactation, only indicates that goats are 130% more economical than cattle and 123% more economical than sheep, whereas sheep are 7% more economical than cattle (Acharya and Patnayak, 1974).

ROLE OF DIFFERENT LIVESTOCK SPECIES

The contribution of livestock to desertification is relatively small as compared with the climatic and human factors. The climatic and human factors are specially related to the utilization of marginal and sub-marginal lands for crop-farming, the felling of trees for fuel and timber and the mismanagement of the livestock. The plasticity of the livestock enterprise due to the possibilities of increasing or decreasing the livestock numbers and their mobility has prompted more and more people in the arid region to adopt livestock-farming. This factor, coupled with the utilization of the grazing-land for crop-farming, has resulted in serious problems of overgrazing, thus adding to the forces causing desertification. The number of livestock per unit area in this region is very high, and it is necessary to reduce their numbers. This would, however, be possible without detriment to the economy of the region if the productivity of animals per head is considerably improved.

Among the species of livestock in the arid region, sheep would perhaps contribute the maximum to soil erosion because of their close-grazing habit. Goats prefer browsing and will graze only under conditions when nothing is available for browsing. They are not so selective as sheep and would consume a wide variety of vegetation, especially weeds, shrubs, bushes and young trees. Because of their ability to utilize such vegetation, goats are able to thrive better, whereas cattle and sheep may starve when grazed on extremely poor rangelands. This fact is reflected in a tremendous rise in goat population in the arid region relative to the other two species.

LIVESTOCK POPULATION TRENDS

The population of different livestock species, according to the 1971–72 Census in the arid areas of the three states, viz. Rajasthan, Gujarat and Haryana, is presented in Table 1. Sheep and goats contribute the maximum (68%) to the total livestock population in Rajasthan, whereas in Gujarat and Haryana, cattle and buffaloes contribute the maximum to animal population. The population of goats as a percentage of the total livestock population is quite sizeable in the arid regions of both Rajasthan and Gujarat. The population trends of different livestock species from 1951–72 in the arid regions of Rajasthan and Gujarat are given in Figures 1 and 2 respectively. There is an overall increase in the population of all the livestock species during these years. However, the largest increase is in the population of goats, closely followed by that of camels in Rajasthan, followed by that of goats and buffaloes in Gujarat and followed by that of cattle in Haryana. The increase in the population of goats, both in Rajasthan and Gujarat, has been phenomenal, in spite of the fact that there have been serious droughts during the last quinquennium. This fact shows the better adaptability of goats to such conditions. The increase in the number of buffaloes indicates the availability of irrigation facilities in some of these areas and the better performance of buffaloes as dairy animals under the system of mixed farming.

PRODUCTIVITY OF THE LIVESTOCK

Although a large percentage of livestock in the arid region, like any other region of the country, are nondescript, there are some important dairy (Tharparkar, Rathi, Gir), draft (Kankarej,

Table 1. Livestock population* (000) in the arid districts of Rajasthan, Gujarat and Haryana

State	Cattle	Buffaloes	Sheep	Goats	Camels	Total
Rajasthan	3,481 (27·9)	1,109 (24·1)	5,249 (61·3)	5,814 (47·8)	624 (83·7)	16,287 (41·9)
Gujarat	280 (4·3)	135 (3·9)	150 (8·7)	250 (7·8)	11 (17·5)	826 (5·5)
Haryana	514 (20·9)	575 (22·8)	206 (44·8)	190 (39·6)	91 (68·4)	1,576 (25·1)

Note : The figures in parentheses indicate the population of a particular species in the arid region as a percentage of the total population of that species in the State.
*1971–72 Census.

Nagauri), and dual-purpose (Haryana) breeds of cattle. The age at the first calving of these cattle is high and they

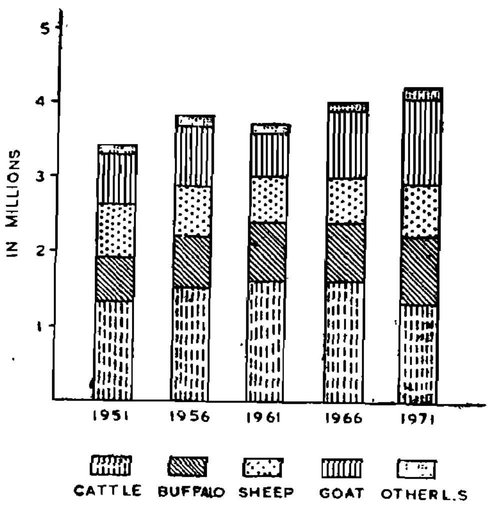

Fig. 1 Livestock population in arid districts of Gujarat

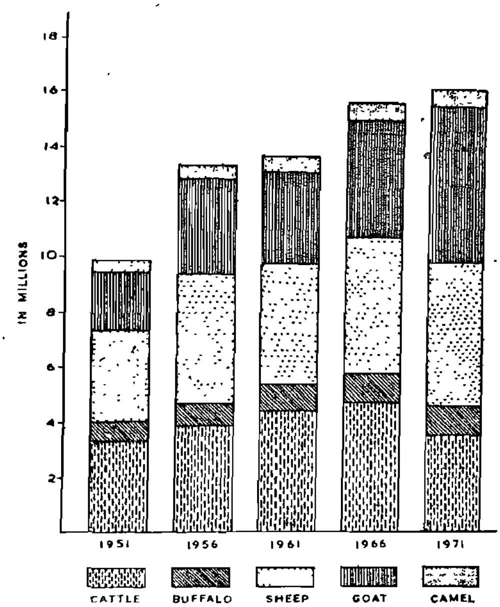

Fig. 2 Livestock population in arid districts of Rajasthan

have a low milk-production level, short lactation and long calving interval. The buffaloes are mostly of the Murrah breed or its grades and of the Mehsana breed, which are good dairy breeds. Their average milk production is better than that of cows, but they are seasonal breeders and have poor reproductive efficiency.

The important breeds of sheep in the region are Chokla, Pattanwadi, Magra, Marwari, Nali, Pugal and Jaisalmeri. The first two breeds produce medium apparel or good carpet-quality wool, whereas the other five breeds produce medium to good carpet-quality wool. Most of these breeds are lighter in body-weight and produce small lamb crops and have lighter fleeces. However, compared with the breeds of sheep in other regions of the country, their production of wool and its quality are superior. The important breeds of goats in the area are Marwari, Jhankrana, Sirohi, Beetal, Jamnapari and Barbari. Jamnapari and Beetal are heavier and taller breeds; Barbari is a short and light breed, and the other breeds are medium in size and body-weight. Most of the breeds are highly prolific and twins and triplets are quite frequent. The goats are primarily used for meat, which is preferred in the greater part of the country. They have a poorer milk-production level than the exotic dairy goat breeds. Some of the these breeds, e.g. Marwari, produce hair which is shorn and has a good export market.

POOR PRODUCTIVITY OF THE LIVESTOCK

The major reason underlying the low productivity of livestock in the arid region is the lack of adequate feed resources. Not only the quality of grazing and supplementary feed available from crop residues is poor, but even the total dry-matter requirement is not being met, in addition, there has been indiscriminate breeding and little effort in effecting any genetic improvement. The stock-watering facilities also are very inadequate in the greater part of this region and, wherever available, the water is brackish. The lack of grazing and stock-watering resources force the livestock-breeders to resort to migration to distant places in search of them. Some breeders are continually on the move, whereas others follow definite migratory routes to the seasonal grazing-areas and return to their permanent abodes during the monsoon season. The large-scale migration of the livestock results in tremendous hardship to the livestock-breeders and to the livestock themselves. It further makes it difficult to take up any livestock-improvement programmes. These livestock are exposed to the hazards of disease and there are serious marketing problems. Because of the latter, the breeders do not show any serious interest in adopting stock-improvement measures.

In the arid region of Rajasthan, the estimated forage (dry matter) availability from the rangeland, top feeds, crop residues, etc. is about 15.41 million tonnes against the total dry matter requirement of 17.46 million tonnes for the existing livestock population, showing a shortfall of 2.05 million tonnes. Similar would be the situation in the arid regions of Gujarat and Haryana. About 80–90% of the rangeland is in a poor to very poor condition and some of the land under good vegetation cover is not fully utilized owing to the lack of stock-watering facilities.

TECHNOLOGY FOR IMPROVEMENT

Numerous experiments have been carried out to develop technology for improving rangelands through protection and soil- and water-conservation practices and on the management of such improved rangelands (Mann and Ahuja, 1975). A carrying capacity of 2.47 sheep per hectare on a year-long basis on poor rangeland has been recommended (Das *et al.*, 1963). The reseeding of rangeland with suitable perennial grasses can improve them faster. Experiments conducted under semi-arid conditions indicate that 5 ewes per hectare can be maintained with expected productivity throughout the year on the reseeded *Cenchrus ciliaris* pasture (Acharya *et al.*, 1975). The introduction of some drought-resistant perennial legumes and fodder-trees, e.g. *Prosopis cineraria* and *Acacia* species, in the pastures will further improve the carrying capacity and production of the livestock maintained on such pastures. To meet the requirement of fodder during the scarcity period, it would be essential to establish fodder banks by harvesting the grasses and tree leaves available during the years of better rainfall. The utilization of technology for enriching low-quality forages and crop residues with urea and molasses can be adopted to meet the nutrient requirements of the livestock.

In spite of the large genetic variability present in most of the production traits, the selection among or within the breeds of livestock available will be slow because of the very low level of performance. It may take about 75 years to double the milk production in the case of cattle through selection. Crossbreeding with superior exotic dairy cattle, e.g. Holstein-Friesian, Brown Swiss, Jersey and Red Dane, improves milk production to an economic level and also improves reproductive efficiency. A level of exotic inheritance around 50% is found to be the most optimum (Acharya, 1970). In the case of buffaloes, selection for milk production within Murrah and Mehsana breeds and the upgrading of other non-descript buffaloes with these breeds would improve their productivity.

Improvement in the production of wool and its quality regarding the apparel wool is possible through crossing the carpet-wool breeds such as Chokla, Pattanwadi and Nali, with exotic fine-wool breeds, such as Merino and Rambouillet. The exotic inheritance at 50% seems to result in the maximum overall improvement (Acharya, 1974). Selection within the other carpet-wool breeds (Marwari, Magra Pugal, Jaisalmeri) for fleece weight and against medullation will improve both the production and the carpet quality of the wool. There will be some improvement in the body-weight through crossbreeding, but such improvement can be fully realized only when such animals are maintained on an adequate level of nutrition.

The improvement of the nondescript goats for milk production can be brought about through upgrading them with breeds such as Beetal, Jhakrana and Jamanapari. The improvement of the three above-mentioned breeds for milk production can be done through selection within the breeds and also by crossbreeding them with exotic dairy breeds, e.g. Alpine and Saanen. Crossbreeding with the above exotic breeds would produce much faster growth and will also reduce the age at which the first kidding will take place.

Heavy losses in livestock productivity occur owing to the mortality and morbidity caused by a number of diseases prevalent in the area. Prophylactic health cover against important endemic diseases through regular vaccination, dosing, dipping or spraying, etc. would reduce such losses. The provision of some shelter, specially during rains and winter, for young animals would improve their chances of survival. The shearing of sheep before the commencement of rains and protecting them from solar radiation until the wool is grown more than 1 cm reduces the yellow staining of it. The yellowing of wool which occurs only during autumn in the case of most of the native breeds in the arid region considerably reduces the market value of the autumn-clipped wool. Washing the animals about a week before shearing improves the efficiency of shearing and the quality of the fleece. Shearing twice a year, machine-shearing, skirting and the primary classing of wool further improve the market price.

As the present development organization cannot undertake the livestock-development programmes up to the extent required, efforts are being made for organizing livestock producers' co-oprratives to provide the input service and to undertake the marketing of the livestock produce and live animals. For the improvement of the migratory livestock, it is necessary to locate service centres on the migratory routes to provide breeding and health service. These centres may also act as fodder and drinking-water resources and advise the farmers on migration.

PROBLEMS REQUIRING FURTHER INVESTIGATION

Investigations are required to study the competition among different livestock species for the utilization of vegetation resources available on the improved rangelands, their relative economic returns, the relative role of different livestock species in causing desertification and to determine the most appropriate species of livestock and their relative proportions on a specific type of rangeland. These studies will help to develop systems of livestock production which will increase the output per unit area of land without bringing about any serious deterioration of the soil. Investigations are also required to develop technology for harvesting and conserving range grasses and top-feeds to meet the feed requirements during the scarcity period.

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SALT AND BY-PRODUCT RESOURCES OF GUJARAT AND RAJASTHAN

M. P. BHATT, G. T. GADRE AND D. J. MEHTA

In spite of several odds, the socio-economic factors have stimulated the growth, establishment and development of various need-based industries in India since Independence. The salt industry is one of them. Salt is one of the major and important raw materials which has played a very significant role in the industrial development and growth of the country. It is a basic raw material for the production of heavy chemicals, such as soda-ash, caustic-soda and chlorine which, in turn, are required by a large array of industries. Having realized the importance of salt, appropriate and expeditious measures were taken by the Government of India to boost salt production in the country. This trend is evident from Table 1, showing increases in production targets since 1951.

Among the various States in India, Gujarat and Rajasthan have larger areas as semi-arid or arid regions. The average rainfall in Gujarat and Rajasthan is 75 cm and 48 cm respectively, and is unevenly distributed, is unreliable and extremely erratic. Droughts and water famines are of frequent reoccurrence. Drought-prone districts of these States occupy one-third and three-fifths of the total area of respective States, as shown in Table 2. However, such a climate has proved to be a boon to the salt industry which has also provided considerable employment for the people residing near the coastal areas.

The principle sources of salt in India is sea-water, inland brine and lake brine. It is proposed to discuss in this paper the sources for the recovery of salt and bittern-based chemicals of Gujarat and Rajasthan under the present status of salt industry.

SALT RESOURCES

Gujarat. All along the coast of Gujarat, Saurashtra and Kutch, salt is manufactured through the solar evaporation of sea-water and subsoil brines. The rapid development of the salt industry in Gujarat

Table 1. Targets of salt production in India during 1951 to 1985

(Figures in million tonnes)

Year	1951-56	1956-61	1961-66	1966-71	1971-80	1980-85
Human consumption	2·07	2·67	3·2	3·6	4·2	4·8
Industrial use	1·00	1·20	1·7	2·3	5·2	6·5
For export	—	—	0·5	0·5	1 0	1·5
Total	3·07	3·67	5·4	6·4	10·4	12·8

Table 2. Drought-prone districts of Gujarat and Rajasthan

	Name of districts
Gujarat	Ahmedabad, Amreli, Banaskantha, Bhavnagar, Broach, Jamnagar, Kheda, Kutch, Mehsana, Rajkot, Surendranagar.
Rajasthan	Barmer, Bikaner, Churu, Jaisalmer, Jodhpur, Ajmer, Banswara, Aspur, Udaipur

Table 3. Salt production in Gujarat and Rajasthan during different years after Independence

(Figures in lakh tonnes)

Years	1951	1961	1971	1972	1973	1974	1975
Gujarat	5·01	17·32	26 34	33·46	39 40	33·66	29 37
Rajasthan	2·52	2·45	4·88	4 83	4·97	4 72	3·15

is due to its suitable climatic conditions, low rainfall, long periods of dry weather, fairly high temperatures and high wind velocity, suitable soil conditions and the availability of an inexhaustible source of sea-water and subsoil brine. Added to these, the required business acumen of the region, good support from the State Government and the Salt Department and the salt-based industries and research efforts of the Central Salt and Marine Chemicals Research Institute have contributed largely to the growth of the salt industry in Gujarat. At present, Gujarat is on the top of the salt-producing States, contributing 60 to 65 per cent of the total salt production in the country (Table 3).

Marine salt resources. Important areas based on solar evaporation of the sea-water are Jamnagar, Kandla, Mundra, Jakhau, Navalakhi, Okha, Jafrabad, Bhavnagar, Porbander, Bherai, Maliya, etc. In 1950, Gujarat had 9 big saltworks each producing 50,000 to 100,000 tonnes, and 4 medium-scale saltworks, each producing 30,000 to 50,000 tonnes of salt per annum. Today in 1976, there are 20 major saltworks and 44 minor saltworks. This progress shows the great strides which the salt industry has made in this State. In comparison with Gujarat, the climatological conditions are not suitable in Andhra Pradesh, Orissa, West Bengal, etc., and the feasibility of growth of large-scale saltworks appears to be remote. Thus Gujarat still remains in the forefront as a major salt-producing State.

The method of manufacturing salt is based on fractional crystallization. It consists in the intake and storage of sea-water in reservoirs through the natural tide or pumping or both, followed by gradually condensing it to the salt (NaCl)—saturation level, say 24°-25° Bé and then feeding it to well-prepared crystallizing pans. The salt is crystallized between 25° and 30° Bé and a layer of 5 to 8 cm is allowed to grow with a multiple irrigation system before harvesting. Three to four crops of salt are harvested per season. The present production of marine saltworks is about 26 to 30 lakh tonnes per annum (Table 4).

Inland salt resources. The Little Rann

Table 4. Production of salt and the average quality of salt produced in different areas of Gujarat and Rajasthan

(Figures in lakh of tonnes)

	Name of Area	Years 1972	1973	1974	Average quality of salt produced percentage on dry basis NaCl	Ca	Mg	SO_4	Insol.
Gujarat	Jamnagar	14·18	14·74	14·51	98·3	0·17	0·22	0·61	0·09
	Rajkot	1·74	2·46	1·93	98 2	0·17	0·16	0 51	0·19
	Bhavnagar	1·72	1·67	1·41	98·2	0·13	0 34	0 75	0·07
	Kutch	5 11	6·52	5·16	97·6	0 16	0·27	0·77	0·04
	Junagadh	1 70	2·24	1·14					
	Amreli	1·39	2 41	1·99	98·6	0·12	0·13	0·43	0 08
	Kaira	0·22	0 24	0 20		Not available			
	Bulsar	0 79	0 66	0·47		Not available			
	Kharaghoda	3 08	4 71	3·28	96·5	0·2	0 1	0 5	0 1
					to	to	to	to	to
	Kuda	3·53	3·75	3·57	98 0	0·5	0·3	1·2	1 4
	Total:	33·46	39 40	33·66					
Rajasthan					NaCl	Na_2CO_3	Na_2SO_4	$+NaHCO_3$	Insol.
	Sambhar	1·79	2·54	1·65	89·1	0·70	0·50		0·7
	Didwana	0 68	0·46	0·67	Good qlty 96 8 Infe-rior 85·0 to 90·0	1 87 7 to 11	0·23 2 to 3		— —
	Phalodi	0·96	0 77	0·82	97·3	1·1	—		0·5
					NaCl	$CaSO_4$	$MgSO_4$	$MgCl_2$	Insol.
	Pachbhadra	0·44	0·13	0·43	97 to 98	0·2 to 1·4	0 5 to 0·9		0·12 to 0·19
	Sujangarh	0 35	0·30	0·44	98·2	0·46	0·98	0·16	0·18
	Kuchaman	0·52	0·73	0 63		Not available			
	Pokaran	0·09	0 04	0 08		Not available			
	Total:	4·83	4·97	4·72					

of Kutch is another important source, contributing 20 to 25 per cent to the salt production of the State. Geological studies have indicated that the natural subsoil brine in the Rann of Kutch has originated from the concentration of sea-water. The Little Rann of Kutch, once a navigable sea, has been raised by natural convulsions and earthquakes, and covers 3,200 sq km. Its natural depression gets inundated every year by high spring tides and by a few rivers during the monsoon and thus the subsoil brine-table is replenished. The dry season, October to May, is availed of for salt production. The brine for salt production is obtained by digging open wells. The composition of brine is akin to that of sea-water, except for the sulphate content, which is low, but the magnesium content is high. The area is largely utilized by small saltworks owned by private parties and co-operative societies. In most of the saltworks, salt is manufactured by using an age-old method. The method consists in fetching the brine of 17° to 20° Bé from a well with a *dhenkava* manually and feeding it to condenser and raising it to 23° to 24° Bé. It is then charged to well-prepared crystallizers of 66 × 33 × 0.3m. The crystallizers are occasionally charged with brine from condensers to maintain the density between 27° and 30° Be' and only one crop is raised at the end of the season. Big crystals or crystal aggregates, known as "Baragara Salt" are obtained. This type of salt has a good market for domestic use in northern India and Nepal. The present salt production and the quality of salt produced in the Little Rann is shown in Table 4.

IMPROVING THE QUALITY AND YIELD OF SALT

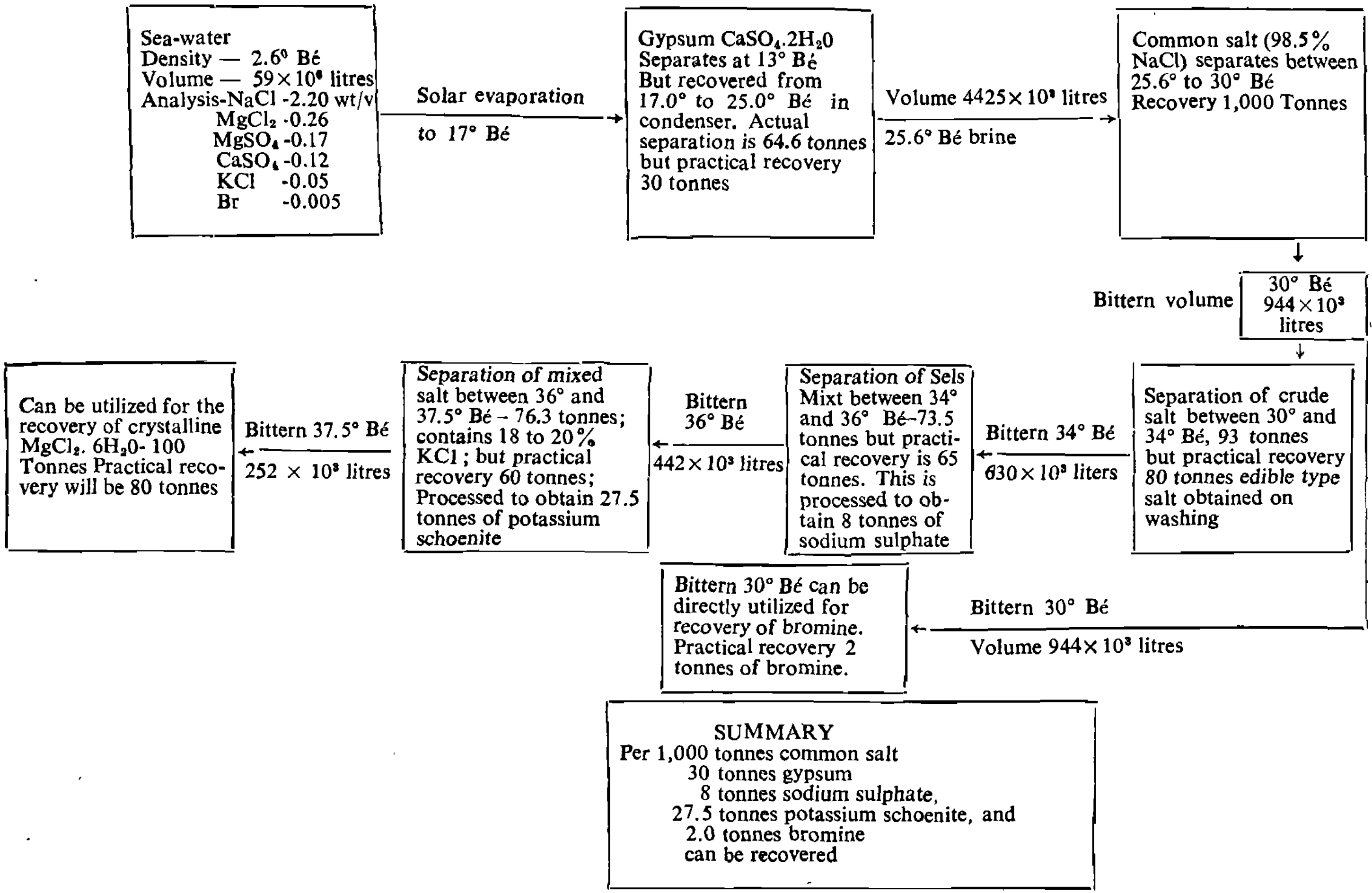
During the early fifties, salt manufacture in many regions of the country was not based on scientific lines. It was mostly handled by non-technical, illiterate *agarias* and the quality of salt produced was much below that required for edible, industrial or export purposes. In 1948-49, the Government of India appointed a Salt Expert Committee which surveyed practically the entire salt-producing area in the country. The Committee reported the methods in vogue at that time and made valuable suggestions to modify them to improve the quality of salt. Consequently, in 1954, the Central Salt and Marine Chemicals Research Institute was established by the CSIR to undertake systematic research and development to improve the quality of solar salt and to increase its yield per acre, to manufacture different grades of salt and to develop economic processes for the recovery of marine chemicals from sea and inland bitterns.

After its establishment, the CSMCRI has been in close contact with the salt industry in India. The Institute has helped to improve the quality of salt and its yield per acre. Today, many large marine salt-

Table 5. Compositions of brines from various sources in India—sea-water, inland lakes and well brines

Percentage on dry basis	Sea-water	Kharaghoda	Kuda	Sambhar Lake brine	Pachbhadra	Didwana
$CaCO_3$	0·345	0 060	0·073	—	—	—
$CaSO_4$	3 600	2·120	1 961	—	2·970	—
NaCl	77·758	70 800	72·342	87·300	85·660	77·190
$MgSO_4$	4·737	2·313	2·320	—	9 440	—
KCl	2·465	2·000	1·250	0·129	—	—
$MgCl_2$	10·878	22·360	21·975	—	1·930	—
$MgBr_2$	0·217	0·347	0·259	0·051	—	—
Na_2SO_4	—	—	—	8·650	—	20·650
Na_2CO_3	—	—	—	3 870	—	0·600
$NaHCO_3$	—	—	—	—	—	1·560
$CaCl_2$	—	—	—	—	—	—

Table 6. The recovery of salt, co-products and marine chemicals from sea-water (Basis : 1,000 tonnes of salt)



works in Gujarat have achieved a yield of 50 to 60 tonnes per acre and the average purity of salt is over 98 % (Table 4).

BY-PRODUCTS RECOVERY

Based on the phase equilibria on the progressive solar evoparation on sea-water, various evaporites are separated by keeping strict control on density (Table 5). The large salt-works in Gujarat are comparatively well laid out and are capable of processing the sea-bittern to obtain various coproducts evaporites. The quantum of the recoverable coproducts based on 1,000 tonnes of solar salt production is shown in Table 6. These coproducts have to be further processed to obtain edible salt, epsom salt, sodium sulphate, potassium fertilizer and magnesium chloride. Bromine can be directly recovered from 29° Bé bittern, whereas gypsum separates from brine in the density range of 17° to 24° Bé. Processes for the commercial exploitation of these evaporites and the economic recovery of the marine chemicals from them have been successfully developed by the CSMCRI for the benefit of the salt industry. The potential recovery of various chemicals over and above the salt by large saltworks in Gujarat is shown in Table 7, which also shows the value of recoverable chemicals. Based on the CSMCRI know-how, it is possible to establish marine chemical complexes at Jamnagar and Kutch, where a number of large saltworks exist.

The recovery of bittern evaporites from saltworks in the Little Rann of Kutch requires careful and extensive planning, keeping in view the collection of bittern at some suitable central place from a large number of small and scattered saltworks. Based on the availability of bitterns, the potential recovery of 7,000 tonnes of potassium fertilizer has been reported. Similar possibilities exist in the Great Rann of Kutch where the subsoil brines are known to contain potassium chloride. Exploratory work is being done by the CSMCRI in collaboration with the Geology and Mining Department of the Gujarat State and the Geological Survey of India.

Rajasthan

Many parts of Rajasthan are rich in saliferous earth and sub-soil brine which

Table 7. Potential marine chemicals recovery from brines and bitterns available from large marine saltworks in Gujarat

Basis: 15 lakh tonnes of salt production per annum by large saltworks

Sr. No.	Name of evaporite	Quantity of evaporite in tonnes	Chemical that can be recovered from (2)		Total value of recovered chemical. Rs in lakhs
			Name	Quantity in tonnes	
	1	2	3	4	5
(i)	Gypsum	45,000	Washed gypsum	40,000	12
(ii)	Crude salt	1,20,000	Edible salt	96,000	19
(iii)	Sel's Mixt	1,05,000	Sodium sulphate	12,000	150
(iv)	Mixed salt	90,000	Potassium schoenite	40,000	240
(v)	Magnesium chloride	37,500 (Considering 25% bittern utilization)	Washed and upgraded magnesium chloride crystalline variety	30,000	150
(vi)	Bittern* 30° *Be'*	70·8 × 10⁷ litres (50% bittern utilization)	Bromine	1,500	270

* The quantity of bittern is expressed in litres in column (2).

are exploited for the production of salt. Important among these are the Sambhar lake, Didwana, Pachbhadra, Phalodi, Kuchaman and Sujangarh.

Sambhar Lake. The Sambhar lake is the largest salt source in Rajasthan situated in latitude 26° 58′ N and longitude 75° 5′ E. The lake proper is 40 km in length and 3 to 10 km in width, covering 235 sq. km. During the monsoon, the lake gets filled up to a depth of 50 to 90 cm depending upon the rains. The lake is not permanent, but recedes and dries up during the dry season. The bed of the lake is covered with saliferous black silt which is 3 to 5 m deep at the edges and 19 m at the centre of the depression. The soluble compounds of the mud consist largely of sodium chloride, with an appreciable quantity of sodium sulphate and sodium carbonate and bicarbonate. The composition of the brine is given in Table 5.

Climatic and soil conditions are quite favourable and salt is being manufactured here from ancient times. The present process is fairly simple and is based upon the density control at different stages. When the lake brine reaches 3° to 5° Bé, it is transferred to reservoirs and condensers situated at the periphery of the lake. Here it is condensed to 25° to 26° Bé and then charged to crystallizers (3 to 7 acres). Salt is allowed to crystallize up to 29° Bé by a multiple irrigation system and a single crop is harvested at the end of the season. To increase the production of salt, brine from percolation canals is also mixed with the lake brine. The analysis of salt obtained is shown in Table 4. The average production of salt for the last so many years varies from 2 to 2.5 lakh of tonnes per annum.

Didwana. Didwana is situated in the Nagaur District, at about 65 km northwest of the Sambhar lake. This depression is 6.5 km long and 2.5 km wide, covering an area of 16.25 km². The soil of the basin is black saliferous silt similar to that of the Sambhar lake and extends to a depth of 3 to 5 metres. Brine for the manufacture of salt is obtained by digging the wells 4 to 5 m deep and 2 m in diameter and are renovated every year. The density of the brine ranges from 15° to 23° Bé and is rich in sodium chloride and sodium sulphate. The analysis of the brine is given in Table 5.

The manufacturing operation does not start till the end of February owing to the possibility of sodium sulphate being deposited along with the salt during the cold winter. The brine, as obtained from the wells, is charged directly to crystallizers (20 m × 60 m or 16 m × 40 m) without prior condensation. The first crop is usually taken after 60 days and the subsequent crops are harvested at intervals of 20 to 25 days. The bitterns are not discharged from the crystallizer. Consequently, the salt of inferior quality is obtained as the season progresses. The analyses of various grades of salt obtained are given in Table 4. The annual production varies from 50,000 to 70,000 tonnes.

Pachbhadra. Pachbhadra is situated 90 km from Jodhpur and 240 km south-west of the Sambhar lake. It is an oval depression, 11-12 km long and 5-11 km wide; however, salt production is resorted to on a tract of 3 × 9 km. The brine occurs at a depth of 3-3.5 m and its density ranges from 14° to 21° Be′. The analysis of brine is given in Table 5. It will be seen that it is somewhat similar to sea-water.

Salt is manufactured here in a peculiar way. In the subsoil tract, the pits of 130 × 30 × 3–5 m are excavated and brine is allowed to percolate from sidewards and upwards through the pit-bed. About 60 to 90 cm of brine is collected in the pit and is evaporated as the result of solar heat. The salt starts crystallizing at 25° Bé and the crystallization of the salt and the incoming of brine continue. After a salt-bed 60 to 75 cm thick, is formed, it is harvested. It is not possible to separate the impurities from the salt, as there are no separate stages, and the quality of the salt obtained is not uniform and good. The analysis of the salt is shown in Table 4. The average production of salt in this area is about 40,000 tonnes.

Phalodi. Phalodi is situated between

Jaisalmer and Bikaner, about 112 km from Jodhpur. It is a depression of 8 × 4.8 km. Formerly, saltworks situated here were closed down because of an inadequate market for salt, but since 1958-59, the land has been leased to many private salt manufacturers. The method of manufacture is more or less similar to that of Didwana.

The present salt production is about 50,000 to 60,000 tonnes per annum.

Kuchaman and Sujangarh. These sources are comparatively recent, and salt production was started only a few years back. Kuchaman is situated about 32 km away from the Sambhar lake and comprises about 10 small saltworks, producing about 60,000 to 70,000 tonnes of salt, whereas at Sujangarh, 30,000 to 40,000 tonnes of salt is manufactured.

BY-PRODUCTS FROM RAJASTHAN SALT RESOURCES

The composition of brine of the Sambhar lake, Didwana and Phalodi differs from that of sea-brine. Here, the main constituents are sodium chloride, sodium sulphate and sodium carbonate. On the other hand, the brines of Pachbhadra and Sujangarh are akin to sea-water. Efforts have been made to recover sodium sulphate and burkite from the Sambhar and Didwana bittern, based on the work carried out at the CSMCRI.

Sambhar Lake. The present production of salt from the Sambhar lake varies from 2 to 2.5 lakhs of tonnes. From the bitterns available from this source, about 15,000 tonnes of sodium sulphate, 8,000 tonnes of sodium carbonate and 40,000 tonnes of good-quality salt can be prepared. If the bittern is subjected to solar evaporation, the first fraction obtained is the substandard salt unifit for human consumption, followed by solid bitterns on complete drying. The typical analysis of the substandard salt, solid and liquid bitterns is given in Table 8.

Seshadri and Buch (1959) worked out a process for the recovery of sodium sulphate, sodium chloride and sodium carbonate. The process consists in the chlorination of bittern to eliminate algae, followed by chilling it to 0°C after adjusting it to a suitable composition. Sodium sulphate decahydrate separates and it is dehydrated with solar energy. The residual brine is subjected to solar evaporation till the concentration of sodium carbonate reaches 7 per cent (w/v), whereby pure sodium chloride is obtained. Finally, the desalted bittern is carbonated to obtain sodium bicarbonate which is decomposed to get sodium carbonate. This process has been further improved by enriching the sulphate content of the bittern by reacting it with powdered gypsum (100 B.S. mesh) in the solution phase. Practically, most of the sodium carbonate is converted into sodium sulphate. The resulting solution, after settling, is chilled at 0°C to crystallize out sodium sulphate decahydrate which is subsequently solar-dehydrated to obtain anhydrous sodium sulphate. The overall recovery is 95 per cent with purity up to 98 per cent.

Table 8. Analysis of liquid bittern, substandard salt and solid bitterns

	g/100 ml	% by wt. on dry basis	
	Liquid bitterns	Sub-standard salt	Solid bitterns
NaCl	19 5–21·0	91·5	66·1
Na_2SO_4	6·5– 7·5	7·5	30·1
Na_2CO_3	2·8– 3·2	0·6	2·0
$NaHCO_3$	0·8– 0·9	—	—
Insolubles	—	0·4	1·2

Sapre and Baxi (1959) worked out the process for the recovery of burkite from the Sambhar bittern. By a suitable adjustment of the concentration of bittern and heating it to 100°C, a double salt burkite ($2Na_2SO_4.Na_2CO_3$) is separated and the mother-liquor on, solar evaporation, yields 97 to 99 per cent pure salt. Burkite can be further processed by using the modified trona process to recover sodium sulphate and sodium carbonate. The process is claimed to be economically feasible.

Malhotra and Acharya (1964) of Hindustan Salts Ltd., developed the process for the recovery of burkite. Solid bittern is digested with hot water under controlled conditions to leave a residue having a composition similar to that of burkite (Na_2SO_4: 70-75%, Na_2CO_3: 22-25%, NaCl: 2%). A pilot plant producing 250 to 300 tonnes of burkite per annum, utilizing this process is in operation at the Sambhar lake.

Didwana: Didwana brine at 24° Be′ (Table 9) is richer in sodium sulphate than the brine of the Sambhar Lake.

Table 9. The analysis of the Sambhar and Didwana brine at 24° Bé

g/100 ml	Sambhar	Didwana
NaCl	19·0	16·0
Na_2SO_4	3·1	7·0
Na_2CO_3	1·4	1·0

Owing to extreme climatic conditions, the Didwana brine gets chilled during winter and sodium sulphate separates out as decahydrate. For the last 6 to 7 years, a plant based on the artificial chilling of Didwana brine, producing about 20 tonnes of sodium sulphate per day, is in operation at Didwana. The annual production is about 5,000 to 5,200 tonnes.

After the recovery of sodium sulphate, the residual brine is subjected to solar evaporation to obtain good-quality common salt. It has been estimated that if all the brine available at Didwana is processed for the recovery of sodium sulphate, about 15,000 to 20,000 tonnes of it, can be obtained, and simultaneously the quality of common salt can be very much improved.

No efforts have as yet been made to recover by-products from these sources, probably because of salt production on a small scale. As these brines have a composition similar to that of the sea-brine, the processes developed by the CSMCRI can be made use of for the economic recovery of chemicals by establishing a co-operative sector, so as to pool the raw material at a central place for processing it.

CONCLUSION

The availability of suitable climatic and soil conditions and ample quantities of brine and other socio-economic factors have gone a long way in establishing and developing the salt industry in Gujarat and Rajasthan. Owing to the unique and favourable location for manufacturing salt through solar evaporation of sea-water and inland brines, Gujarat will continue to remain a major contributor to salt production in the country. In spite of increased salt production up to 33 lakh tonnes per annum, sincere efforts are yet to be made for the recovery of by-products by the salt-manufacturers. The CSMCRI technical know-how for the recovery of most of the marine chemicals has been proved to be effective and useful in the case of commercial plants.

The production of salt at the inland salt works at Kharaghoda and Kuda is about 7 lakhs of tonnes. Only a small quantity of bittern is used at present by the Pioneer Magnesia Works for the production of fused magnesium chloride. Hindustan Salts Ltd. is now taking steps to install a 500-kg-per-day bromine plant (150 tonnes per annum) by utilizing the CSMCRI know-how. Systematic and planned efforts will be necessary for the utilization of inland bitterns for the recovery of potassium fertilisers.

The salt sources of Rajasthan produce at present 4 to 4.5 lakhs of tonnes of salt.

The production of salt is solely dependent upon rainfall. Insufficient and excessive rainfall may hinder salt production considerably. In spite of these, the salt industry has shown a steady progress.

Sodium sulphate is the principal by-product of Sambhar, Didwana and Phalodi resources. A plant of 20 tonnes of sodium sulphate per day is under production at Didwana for the last 6 or 7 years, whereas the pilot plants producing 150 tonnes of sodium sulphate and 300 tonnes of burkite per annum are under operation at Sambhar. It is possible to recover 25,000 tonnes and 15,000 to 20,000 tonnes of sodium sulphate at Sambhar and Didwana, if full utilization of bitterns and brines available at these places is carried out. Research and development are necessary to recover by-products from other sources, viz. those at Pachbhadra, Sujangarh and Kuchaman.

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31

THE UTILIZATION OF WIND ENERGY AND WIND REGIMES OF ARID AREAS IN INDIA

S. K. TEWARI

A renewable source of energy, associated with the movement of air masses, has apparently remained unutilized. However, the limited supplies of fossil fuels and the ecological implication of their utilization, the long gestation period of hydro-electric projects, some uncertainties and rising costs of nuclear power, the desirability of curbing deforestation, etc. provide an opportunity for considering alternative sources of energy. A welcome psychological change is being noticed, as the case is being made by many workers and decision-makers for the appropriateness of energy utilization. The growing awareness for considering the full implications, such as social costs and not merely the market costs of energy business, are providing the much-needed encouragement for the growth of alternative sources of energy. In this study, we shall consider some of these aspects in relation to the possibilities of utilizing the wind power of the arid regions of India. We shall begin with the analysis of energy needs to identify the niche for wind energy and then proceed on to a study of wind regimes of such areas.

WIND ENERGY FOR PROVIDING SHAFT WORK

Wind energy offers exceptional possibilities against other alternatives, provided the windmills are designed to be cost-effective. Cost considerations here should include, in addition to economic costs, some related social costs as well. To arrive at some conclusion in this matter, one needs to study the potential and other characteristics of wind energy. They are discussed below.

Power in the winds is expressed by the formula

$$= \frac{1}{2} \varphi A V^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

where φ = density of the air
A = Cross-sectional areas of the wind stream
V = Wind speed

On the basis of unit area, the power is seen to depend on the wind speed which has been accepted as the main indicating parameter for wind power.

Wind speeds have been noticed to fluctuate from time to time and the energy from winds over a length of time is given by the formula.

$$E = \frac{1}{2} \int A \sum_{i=1}^{N} V_i^3 \, hi \quad \ldots\ldots\ldots 2$$

hi = duration of wind speed V_i
i = N corresponds to the upper limit for the utilization of wind speed (V_N) and its associated duration (h_N)

Energy computations are easily made, using equation-2, if the velocity duration-curves are available.

Fig. 1 shows the annual average wind speeds for some of the locations in Gujarat, Haryana and Rajasthan . To a limited extent, one can infer the relative windiness of one location as compared with that of another. If two places have the same annual average wind speed, these may not necessarily produce the same amount of energy. This is so, because the relation-

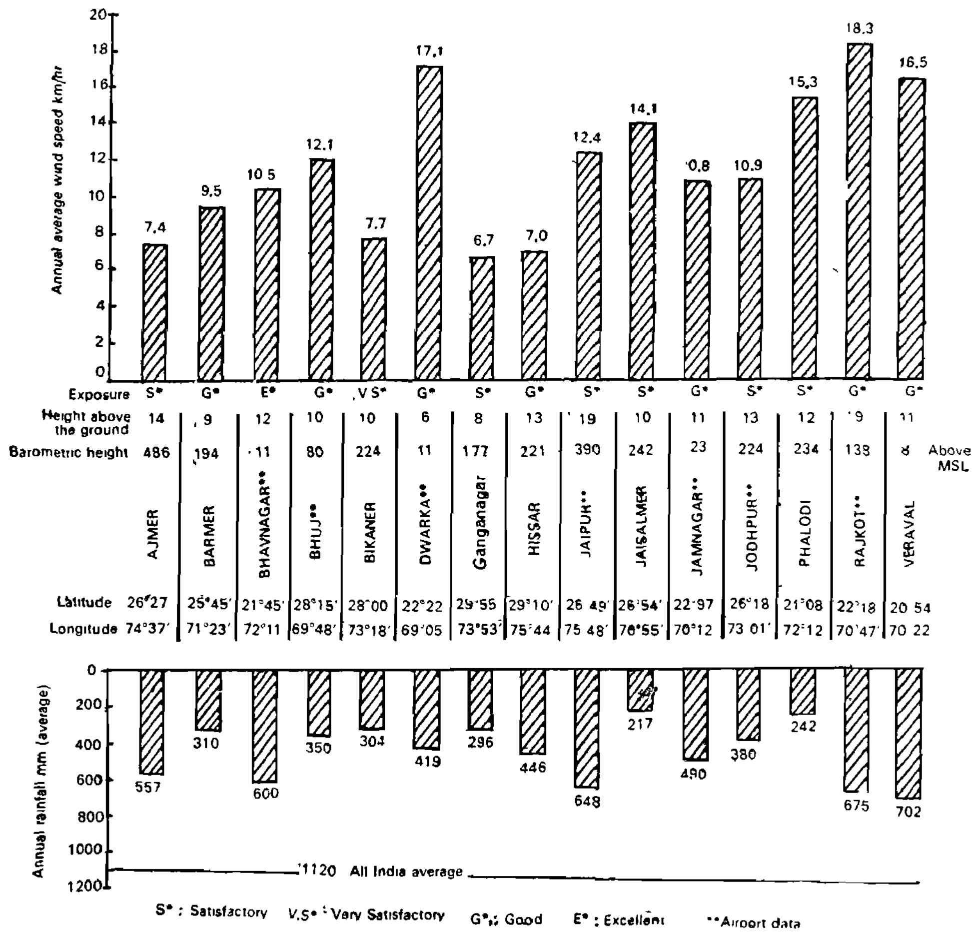

Fig. 1. Average wind speeds for some of the locations in the arid zone. Speeds of 17–18 km/hr are not uncommon in the region

ship between the cube of wind speed and its duration, which may differ from one place to another, even though the average value remains the same. For example, five places having the same annual average speed of 9 km/hr were found to differ in energy potentiality by as much as 75% (Fig. 2). However, the computation of energy potential requires the velocity duration data which are obtained from the installations provided with anemographs. In the arid zone, there are only 7 such installations and the other approximately 12 installations give day (9 hours: 8.30 a.m. to 5.30 p.m.) and night (5.30 p.m. to 8.30 a.m.) averages from which the data in respect of velocity duration cannot be derived. Therefore, in this study, we may have to depend on the monthly and annual average wind speeds only.

THE WIND ENERGY POTENTIAL OF ARID AREAS

Energy could be computed from a velocity-duration curve with the help of equation 2, but we do not have sufficient information on this point for most places in the arid region. We may now try to attempt an indirect technique. For those places, where the velocity-duration data are available, we can determine the rated design speed which could maximize production of kilowatt hours of energy per kw installation. Windmills rated for a particular wind speed do not generate substantial energy while responding to lower speeds. We may, therefore, neglect this contribution. Also, with the regulating mechanisms, the full output is maintained at speeds above the rated value up to the limit of the safe-operating wind speed. This means that if we select a design speed of 20 km/hr the same power is also generated at higher speeds, such as 30 and 40 km/hr. With this assumption, an attempt was made to calculate the design speeds for those places, not necessarily in the arid zone, where the velocity-duration data were obtained earlier. Fig. 3 gives the information relating to the annual average speeds with the associated design speeds that maximize energy output, utilizing the criteria mentioned above. Fig. 3 also gives the number of hours per year one would get the rated output, if a particular design speed was selected.

With reference to Figs. 1 and 3, we find that some locations in the districts of Rajkot, Junagadh (location: Veraval) and Jaisalmer obtain an annual average exceeding 14 km/hr, which would permit one to select a rated speed of 25 km/hr and obtain a rated output for more than 1,200 hours per year. The annual speed of Dwarka may be combined with that of Jamnagar and thus obtain a mean of 14 kph, which may be taken as the representative figure for the entire Jamnagar District. Similarly, for the district of Jodhpur, the combining of the data obtained at the Jodhpur Airport and Phalodi gives a mean value of 13 km/hr. With reference to Fig. 3 we may select 25 kph as the design speed for the districts of Jamnagar and Jodhpur.

For Barmer, Bhavnagar, Jaipur and Kutch districts, we may select the rated speed as 25 km/hr which would allow the generation of the rated output for

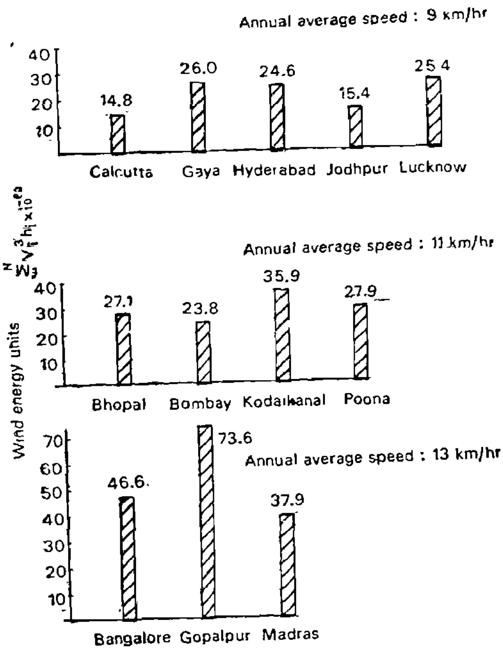

Fig. 2. Average wind speeds do not necessarily reflect wind energy potentiality of a place.

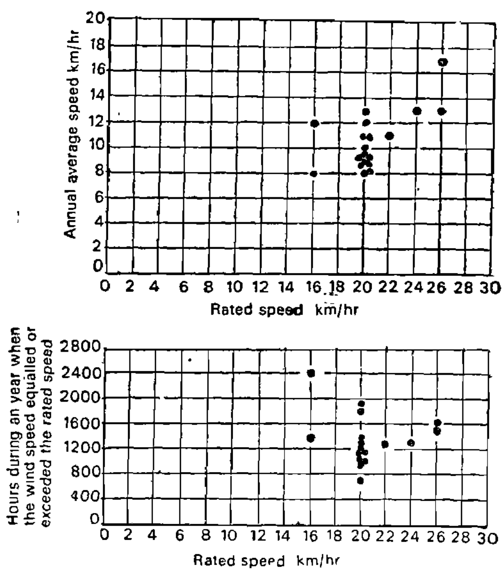

Fig. 3. Rated wind speeds, annual average speeds and the number of hours of full output operation per year

about 1,200 hours per year. We may not consider here other places for which the annual average speed was less than 9 km/hr.

It is necessary to note that it is not quite correct to say that not enough wind energy is available in the Ajmer, Bikaner, Ganganagar and Hissar districts. Only the places where the wind data were so far collected were not the windy ones. The possibility of locating the windy sites in such districts cannot be ruled out, though in our estimation we may proceed by excluding the consideration of these areas.

Let us assume that we wish to install a windmill per hectare. The arid areas generally require about 1 hectare-metre of water per season for food crops, excluding rice. We may assume that water pumped by a windmill for about 300 hours per season could be applied to the fields by some technique, and that the water-table in the arid areas would necessitate an average head of 30 metres for water-pumping. With these assumptions, one calculates a power rating of 2.5 kw at the pump. If one designs an efficient water-pumping windmill to operate with 15% efficiency, the diameters to be swept by the windmill rotors are 12 m with the rated speed of 20 km/hr (5.5m/sec) and 9 m with the rated speed of 25 km/hr (7m/sec). Windmills sweeping a circle of 12 m spaced apart by more than 200 metres would not suffer any serious interference problem.

The area of the districts of Rajkot, Junagadh, Jaisalmer, Jamnagar, Jodhpur, Barmer, Bhavnagar, Jaipur and Kutch totals up to nearly 200,000 square kilometres. If 10% of this area, which is 20,000 square kilometres or 2 million hectares, is farmed with windmills, the installed power capacity amounts to 5 million kilowatts, more than two and a half times the existing combined capacity for electricity generation of Gujarat and Rajasthan.

NEED TO COLLECT THE WIND DATA AT THE SITE

While examining the data displayed in Fig. 1, it may be understood that this information is not quite relevant to the recommending of wind-power utilization for the region. Sites for installing anemometers were selected from several viewpoints, their usefulness for wind-power utilization may have at the most remained one among the several factors. Wind speeds, as measured at a particular location, are considerably influenced by the roughness of the surrounding terrain. Fig. 4 shows that large variations in wind speeds can be expected even between the locations within 10–15 km of each other. The height of the anemometer above the ground level also introduces a need for the interpretation of the data recorded at a particular installation. Substantial efforts have been made for studying this aspect and power law coefficients have been determined for several types of terrains. For instance, if the surrounding area is free from all obstacles, such as buildings and trees, the following equation can be applied.

$$V_1/V_2 = (h_1/h_2)^a \quad \ldots\ldots.3$$

where V_1 = wind velocity at a height h_1 above the ground level

V_2 = wind velocity at a height h_2 above the ground level

a = power coefficient

= 0.16 for open terrain 4

= 0.40 for very rough terrain with large buildings surrounding the point of measurement 4

In principle it is possible to take account of the changes in the type of terrain and thus extrapolate the wind data from one place to another. In practice this is quite tedious and not quite dependable. It is generally desired that data are collected for a place where one wishes to install a windmill. This collection of the data is considered essential if one envisages installing a single large windmill or a cluster of them and take advantage of the uninterrupted winds available at a pre-

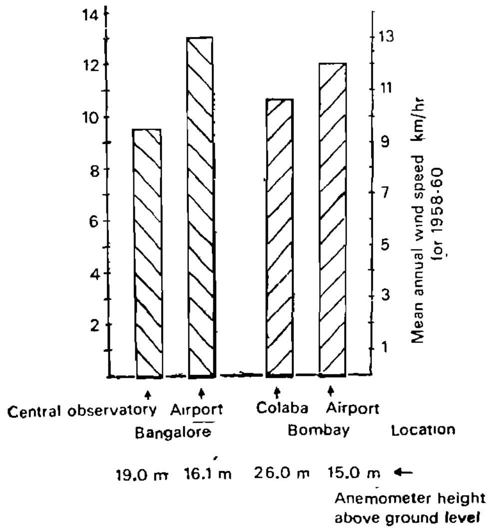

Fig. 4. Spatial variation of wind speeds obtained in the heart of the cities and those at the airport differ

ferred site. In such cases, the record of wind speeds may have to be obtained for an extended period of a few years. For instance, in Oregon, USA, wind-prospecting for locating suitable sites has been carried on since 1973.

METHODOLOGY FOR EXTRAPOLATION FROM LIMITED DATA

Suppose that we have wind data at a station A and wish to predict the behaviour of the wind speeds at another station B, separated by several kilometres from station A. It appears that there is no published study on the extrapolation of the data from station A to station B as a function of the distance, nature of terrain, etc.

A more positive line of inquiry could be to base the prediction of the data obtained for a limited period and extrapolate them for the remaining portion of the year and also from one year to another. This approach is made possible by the relatively predictable behaviour of the winds associated in India with the monsoons—an advantage not normally available at higher latitudes where the bulk of the wind energy comes from storms. The fact is that the results from this approach are of high practical value.

YEARLY VARIATION IN WIND ENERGY AT A PLACE

We may start our inquiry concerning the annual variation in the wind data for a particular place. We may accept the annual mean hourly wind speed as an indicating parameter for the annual energy from the winds. For a location in Bangalore, the values of annual as well as monthly average hourly wind speed were examined for six consecutive years. Statistical techniques were applied to obtain the variation from the mean values of six years for an arbitrarily selected confidence level. From Fig. 5 it can be seen that the variation around the mean value, calculated from 6 years records of annual average speeds, is $\pm 7.4\%$ associated with a confidence level

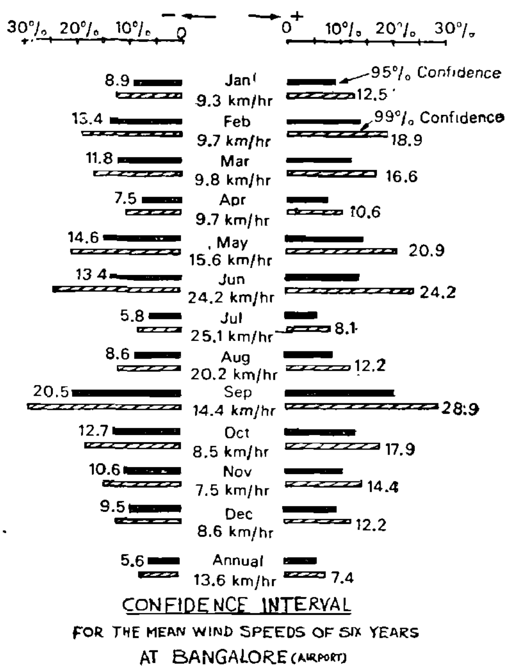

Fig. 5. Wind energy variations in different months (mean of six consecutive years), Bangalore

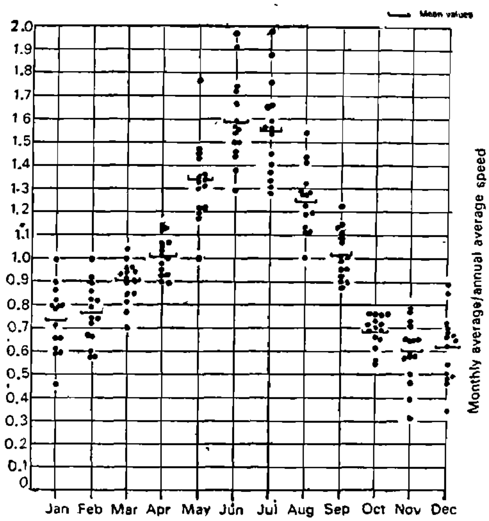

Fig. 6. The energy contribution for each month of the year for 15 locations given in Fig. 1

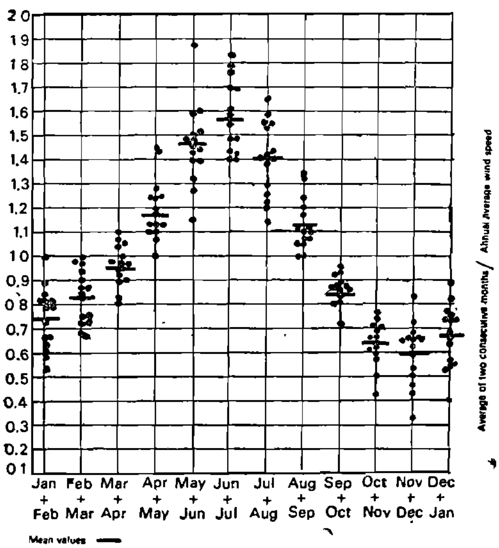

Fig. 7. Wind speed variations determined on the basis of average of two consecutive months

of 99%. This variation should be acceptable in most applications of wind energy. However, it may be noted that variations in monthly average are somewhat higher, as much as ± 28.9% for September. Some applications like the pumping of irrigation water may probably need a better prediction for the monthly output of energy, which may be alternatively taken care of by a slight over-rating of the windmill or by providing for the storage of water.

Since it has been found that at one place, namely Bangalore, the variation in wind energy on yearly basis is not much, one would possibly like to generalize on this aspect for other places, too. Perhaps, it would be more prudent to examine the wind data for some places in the arid areas as well. However, for the time being, we may asume that variations in wind energy from year to year are not intolerably high.

THE PREDICTION OF THE ANNUAL AVERAGE VELOCITY FROM LIMITED OBSERVATION OF WIND SPEEDS

The next inquiry is concerning the prediction of the wind energy expected to be available for the entire year based on observations collected during a particular month at a particular place. The practical benefit lies in saving substantial time and effort, otherwise required in the absence of such a technique. Again, we may accept monthly and annual hourly average wind speeds as the parameters indicating energy. Wind data for 15 places in the arid areas of Gujarat, Rajasthan and Haryana, having annual rainfall of less than 750 mm, were extracted from the Climatological Tables published by the India Meteorological Department for the period 1931-60. The data were normalized in the following manner:

Suppose that the average wind speed at a location in the month of, say March, was 'x' km/hr, and the annual average at the same place was 'y', we divide 'x' by 'y' and obtain a coefficient. This procedure was applied to the values for all other months. For other places, their respective annual average speeds were utilized to normalize their respective monthly averages. For 15 places, the mean values of the coefficient 'x/y' pertaining to each month were calculated. One would be able to appreciate the purpose of this exercise with the help of the following example.

For a new location in the arid region, one measures wind speed for a period of a month, say September, and let us call this average speed 'z' km/hr. The mean value of the coefficient x/y for September, as calculated earlier for 15 locations, was say $(\overline{x/y})$. One can then predict a likely annual average of $z/(\overline{X/Y})$ km/hr. The question that remains to be answered is regarding the confidence associated with this prediction.

Fig. 6 shows a plot of normalized coefficients of monthly average speeds for 15 places for each month of the year. The mean values are also indicated and one observes a significant scatter around the respective mean values.

Fig. 7 gives information which differs from that given by Fig. 5 in that the averages for any two consecutive months of normalized coefficients are plotted. In other words, if $(X/Y)_7$ and $(X/Y)_8$ were the normalized monthly averages for July and August, the ordinate in Figure 7 shows $Y_2 \{(X/Y)_7+(X/Y)_8\}$ and we may call this $(X/Y)_{7-8}$. Now suppose that we record wind speeds at a new place during August and September and calculate the average for these two months. Let us call this speed V_{7-8}. From Fig. 7 we note the mean coefficient for the two consecutive months of August and September as $(\overline{X/Y})_{7-8}$. The predicted annual average speed is given by $V_{7-8}/(\overline{X/Y})_{7-8}$.

For obtaining the confidence level on the mean values, we may define intervals of acceptable variation around the means as $\pm 10\%$, $\pm 15\%$, etc. Out of a maximum of 15 cases, the number of cases actually falling within the defined interval of variation would give the confidence level. The probabilities calculated in the above manner are shown in Fig. 8. It is evident that a much better confidence is obtained in $\pm 20\%$ interval and with the averages of two successive months. The confidence level of 90% may be considered quite satisfactory for most practical purposes. For the purpose of noting predictions, better reliance can be placed on wind speeds recorded in months other than November, December, January and February.

While examining Figs. 6 and 7, one observed a positive trend in obtaining higher wind speeds during May, June and July than those obtained during other months of the year. One might feel tempted to do some curve-fitting exercise to obtain an elegant formula giving the mean monthly values against the particular month of interest. Even without a curve one can easily work out the values for monthly average speeds with the help of Fig. 6 or 7, once the annual average has been determined. With this process, information concerning variability in the confidence levels for each month is also retained.

SOME ASPECTS CONCERNING WIND DATA

Shortcoming of the derived averages

For obtaining velocity-duration curves, it is a normal practice to utilize the data in respect of the mean hourly wind speeds. The choice of the hourly average seems to have been guided by the fact that one needs to arrive at stable averages. The time base of an hour would be insensitive to gusts (with the time base of a few seconds) as well as larger atmospheric movements, such as a depression (with the time scale of several hours and at time even a couple of days). It is worth noting that whereas depressions may occur occasionally, the structure of the wind is such that its speed varies almost every instant and this aspect is sometimes overlooked while dealing with derived averages. Slow-running, multi-bladed water-pumping windmills have been found to be less sensitive to the instantaneous variations in the wind speed and quite often do not respond to gusts, unlike the high-speed rotors of low solidity, normally used in electricity generation.

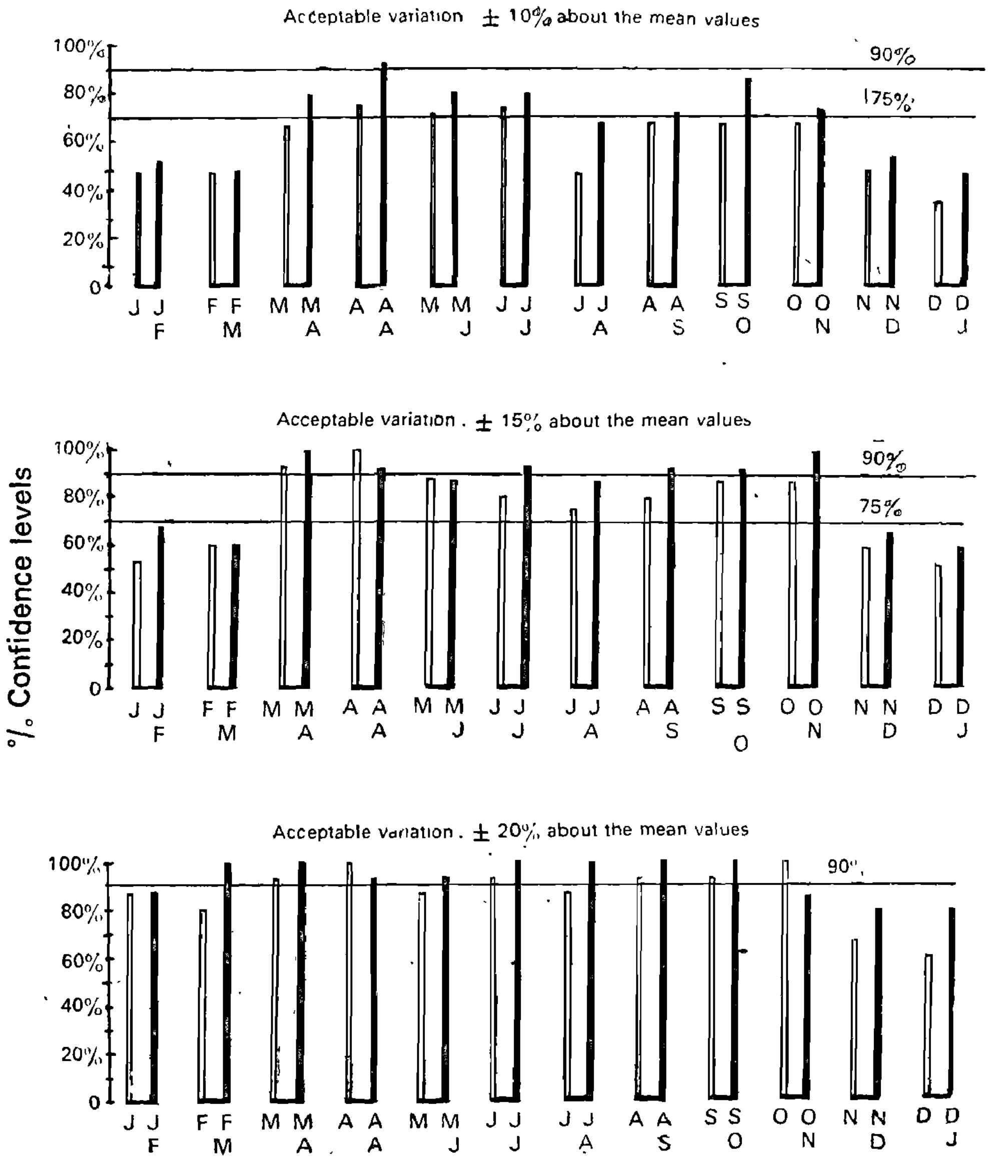

Fig. 8. Prediction of wind energy from limited data, with an error of ± 15 %, the data pertaining to any two consecutive months from May to October would suffice

The data consisting of average wind speeds cannot form a basis for the structural design of windmills. It has been found that the peak gust speed could be 5–10 times higher than the monthly or annual average speeds. Since one of the tasks for a windmill-designer is to minimize the material consumption in the design of a windmill rotor and tower, the importance of a closer scrutiny of wind data cannot be overemphasized. It is also clear that a windmill responding to gusts would deliver significantly more output than what would be indicated by the average speeds.

Changes in wind speed with height above the ground level

A piece of information normally required by windmill-designers is concerning the selection of the height of the windmill towers. According to equation 3, for an open terrain, one would obtain 58% of the free wind speed (obtained immediately after crossing the earth's boundary layer) at 10 metres, 75% at 50 metres and 84% at 100 metres above the ground level. On the other hand, for a place surrounded by a number of tall trees and buildings, the speeds obtainable at 10 m, 50 m and 100 m are 20%, 38% and 50% of the speed of free wind, respectively. These data are useful in cost studies in which case one may like to select an optimum height for windmill towers.

Changes in the wind direction

An examination of the records of instantaneous wind velocity would reveal that, apart from fluctuation in the speed every instant, the direction also changes. During a day, the average direction does not normally alter too much though a variation of ±30 degrees is not uncommon. It would, therefore, appear that windmills without automatic orientation, but with some manual attendance, may also be considered if this arrangement offers reduction in the cost. Of course, this would apply only to large-inertia, multi-bladed, slow-running water-pumping windmills.

Diurnal variation in wind speeds

In arid areas, just like most other places in India, wind speeds are relatively high during the daytime as compared with those during the night. This information is useful in designing multipurpose windmills for pumping water and electricity generation in which case winds of the night could electrify homes, and the strong winds of the day could power water-pumps and other mechanical devices.

Wind-speed and rainfall distribution

Since the bulk of the rainfall in arid areas occurs during the south-westerly monsoon, the need for pumping water from the wells may not be very much during the *kharif* season (July–October). On the other hand, the *rabi* season depends almost entirely on irrigation, but then the winds are not at their best during November to March. The highest wind speeds are obtained during April, May and June, whereas the maximum rainfall occurs during July and August. Thus if the groundwater is available, windmills can do their best to raise a summer crop (March–June) apart from alleviating the drinking-water shortages in the arid areas.

SOME DESIGN ASPECTS CONCERNING THE WINDMILLS SPECIFICALLY FOR USE IN THE ARID REGIONS

Finally we may consider some aspects connected with the designing of windmills specifically for arid areas. First, the water-table is generally lower; a depth of 100 feet is not uncommon. Such a depth necessitates the use of deep-well pumps. A proper design of the windmill rotor to provide desirable torque characteristics is extremely important. The direct coupling of the windmill with a rotodynamic pump is yet to be tried in India, though this alternative is quite welcome for somewhat larger windmills in the 5–10 hp range.

Cost reduction by utilizing suitable materials for the rotor is an attractive possibility. Some experiments with low-cost sail-type windmills have demonstrated the feasibility of such an idea. Whether, in the long run, this is a more cost-effective idea than the conventional metal-bladed design is yet to be established. Similarly, satisfactory furling arrangements have to be developed with the sail-type windmills.

Studies regarding the selection of a safe design speed for towers to withstand sand storms, the optimum height for energy and cost maximization, etc. are required, as these would help to effect some cost savings. Similarly, the possibility of dispensing with automatic directional orientation where periodic manual attendance may be available is worth studying.

Perhaps the traditional water-lifts such as Shadou (counterpoise lifts), *rahat* (the Persian wheel), *mhote* (rope and bucket), etc. could also be powered by windmills as against a complete dependence on human and bullock work in many places. A study for designing suitable windmills and their matching with such devices can also form a useful study.

The survivability of windmills against exposure to marine atmosphere near the coastal areas of Gujarat, and against the dust storms of western Rajasthan requires a proper selection of materials, protective paints and coatings. The designing of foundations for towers in the desert soil would require a more careful attention.

ECONOMICS OF WIND-POWER UTILIZATION

A windmill is a capital-intensive device, requiring a higher initial investment than that for a diesel engine, a pair of bullocks or an electricity connection from a rural electrification scheme. The cash surplus, if any, of the small and marginal farmer is not expected to be invested in a windmill. A farmer can probably raise a loan from the bank or a co-operative institution, but this would mean paying an annual interest of 10–15%. Clearly, it would not be attractive for a normal farmer to accept the windmill option entirely of his own choice.

The government supports rural electrification as a socio-economic programme which often involves subsidizing for electricity availability in rural areas. It would not be out of place to suggest that a similar subsidy could be provided for windmills as well. Apart from the cost of electricity at a point in the main transmission network, an additional investment is required for the transmission line, specifically for electrifying a particular village. So far, when priority for electrification was given to more populous villages located near the cities and the towns, the transmission lines were not required to be laid for long distances. However, for less populated and far-flung villages, transmission lines have to traverse longer distances which are bound to raise the cost of electricity supply. There is a relationship between the length of the transmission line and the associated break-even cost for windmills on a per kw basis. It appears possible to obtain one kw of power for about 1,500 hours a year at most places with a well-designed windmill costing Rs 10,000. A windmill might prove even economical in many cases. Efforts put on designing the cost-effective windmills are likely to pay good returns as well as provide an appropriate, non-polluting, renewable source of energy.

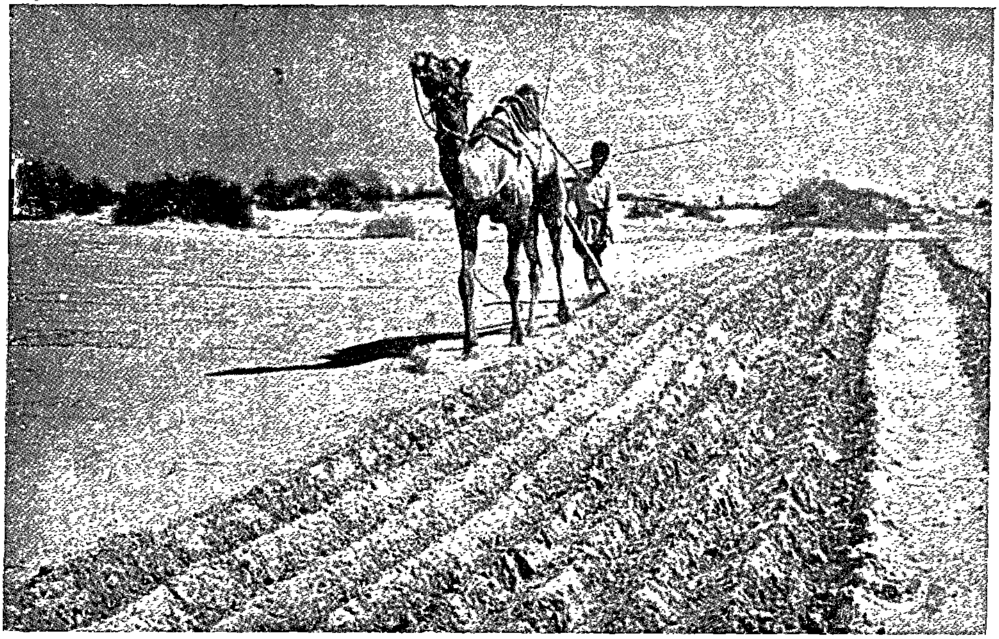

Plate n. Camels are commonly used for ploughing fields in Rajasthan

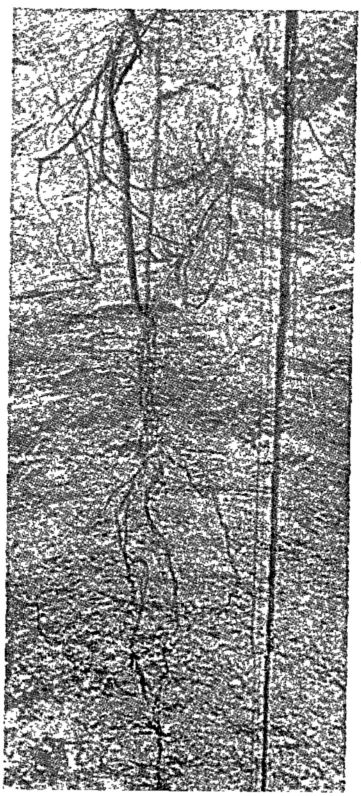

Plate o. Rooting pattern of *ber* (*Zizyphus mauritiana*) in relation to soil profiles having *kankar* pan in arid zones

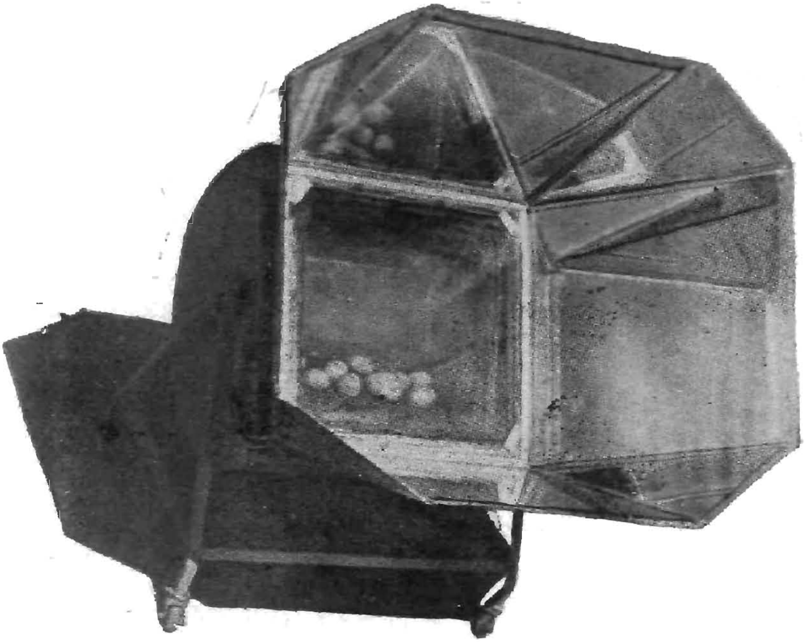

Plate p. A solar oven

Plate q. A *banjara* with his household belongings

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THE UTILIZATION OF SOLAR ENERGY IN THE ARID AND SEMI-ARID ZONES OF INDIA

H. P. GARG

THE arid and semi-arid areas of the world have a uniformly high level of solar radiation throughout the year. These otherwise inhospitable areas, thus, have an inexhaustible supply of pollution-free energy.

The total energy consumption of our country increased from the fuel equivalent of 184.5 million tonnes of coal during 1953–54 to that of 358.7 million tonnes of coal during 1968–69. With the gradual increase in population, our energy consumption is likely to reach a value of more than 500 million tonnes of coal equivalent in the near future. Since the thermal-energy equivalent of one tonne of black coal is 2.9×10^{9} joules, the energy consumption of our country for the year 1968-69 would work out at 0.01×10^{21} joules per annum. The corresponding values for the energy consumption of the world and the USA are 0.3×10^{21} joules per annum and 0.1×10^{21} joules per annum respectively. Thus our total consumption of energy is only 10% of that of the USA, whereas our population is almost three times that of that country. This estimate indicates the very low consumption of energy per head in our country.

The bulk of our energy consumption, unlike in other countries, comes from non-commercial fuels, such as dung, fire-wood and agricultural wastes. Since these fuels can contribute valuable organic matter to the soil of our agricultural fields, and because the cutting of trees causes considerable soil erosion, the use of these non-commercial fuels must necessarily be discouraged.

The exploitation of solar energy offers India a number of distinct economic and technological advantages in contrast with the continued reliance on fossil fuels. First, it is a nondepletable, indigenous energy resource and its exploitation will allow the country to reduce its dependence on foreign oil. Second, it is abundantly available throughout the country, allowing for the decentralization of India's energy and power systems. Third, whereas highly sophisticated technologies exist for its exploitation, numerous small-scale, low-grade, thermal devices are presently available, and they can be produced on a cottage-industry level in India.

DISTRIBUTION OF SOLAR RADIATION

Solar energy is collected either with the help of flat-plate collectors or with focussing collectors. The flat-plate collectors utilize the total solar radiation, whereas the focussing collectors make use of only the direct solar radiation. Hence it is important to know the values of the total solar radiation and the direct solar radiation at normal incidence at a given place.

In India, there are about 30 radiation stations, recording the total solar radiation of a horizontal surface (Rao and Ganesan, 1972). The seasonal mean values of the total solar radiation (cal/cm²/day) on a horizontal surface for various arid and semi-arid regions of the country are shown in Table 1.

The position of the sun in the sky can be known if the altitude angle and the azimuth angle of the sun is known. These angles

Table 1. The seasonal mean values of the total solar radiation (cal/cm²/day)

Station	Arid or semi-arid	Winter (Dec.-Feb.)	Hot weather (Mar.-May)	Monsoon (June-Sept.)	Post-monsoon (Oct.-Nov.)	Annual average
Ahmedabad	Semi-arid	429	611	466	458	491
Bangalore	Semi-arid	461	580	392	400	458
Bhavnagar	Semi-arid	442	618	452	481	498
Hyderabad	Semi-arid	436	544	372	369	430
Jodhpur	Arid	414	612	534	479	510
New Delhi	Semi-arid	363	576	479	420	460
Poona	Semi-arid	459	602	435	461	489

can be computed for a given place at any hour of the day with the help of trigonometric relations, or can be read with the help of a solar chart. A solar chart for Jodhpur has been drawn and is shown in Fig. 1. With the help of this chart, the altitude and the azimuth of the sun and the number of the possible sunshine hours for surfaces of any orientation can be easily found out.

After knowing the components of direct, diffuse and reflected radiations and the various sun-earth relationships, the radiation on the inclined planes can be computed. The total radiation on an inclined plane kept at an optimum tilt has been computed for 10 Indian stations. From these data, it can be concluded that a surface kept at the optimum tilt collects nearly 50% more radiation than what a horizontal surface receives at the northern stations, e.g. Jodhpur and Delhi, and 35% more in the interior peninsular stations, e.g. Nagpur and Poona. For other stations, this increase varies from 20 to 25%.

The total area of the Rajasthan State is 3,38,413 km². This state may be assumed to receive, on an average, about 5,100 kcal of solar radiation per m² in a day. This quantity works out at 18,61,500 kcal/m² per year Thus the total solar radiation received over Rajasthan in a year is of the order of 6,29,955 × 10^{12} kcal. This energy is equivalent to 91,131 million tonnes of coal which is even more than the total energy consumption of the world in a year. Thus the solar energy has a large potential for being used as an energy source in our country.

The focussing type of solar-energy collectors make use of the direct solar radiation. Hence a knowledge of the direct solar radiation at normal incidence at a place is essential for knowing the effectiveness of the focussing collectors. Jodhpur may be taken as a representative place for finding out the potential of solar-energy utilization with focussing collectors. Table 2 shows the mean values of the direct solar-radiation intensities for different seasons for air masses 1 to 5 at Jodhpur. It may

Table 2. The mean values of intensities of the direct solar radiation in cal/cm² min. for different air masses at Jodhpur

Air mass	Winter	Hot weather	Monsoon	Post-monsoon	Annual
1·0	1·44	1·18	1·10	1·34	1·26
1·5	1·22	1·02	0 94	1·16	1·08
2 0	1·08	0·90	0 82	1 00	0·94
2·5	0·96	0·80	0 70	0·90	0 84
3·0	0·88	0·72	0·56	0·82	0·76
3·5	0·84	0·66	0·48	0·74	0·70
4 0	0·70	0·64	0·42	0 70	0·66
4·5	0·68	0 60	0 38	0·68	0 62
5·0	0 66	0·58	0·36	0 68	0 60

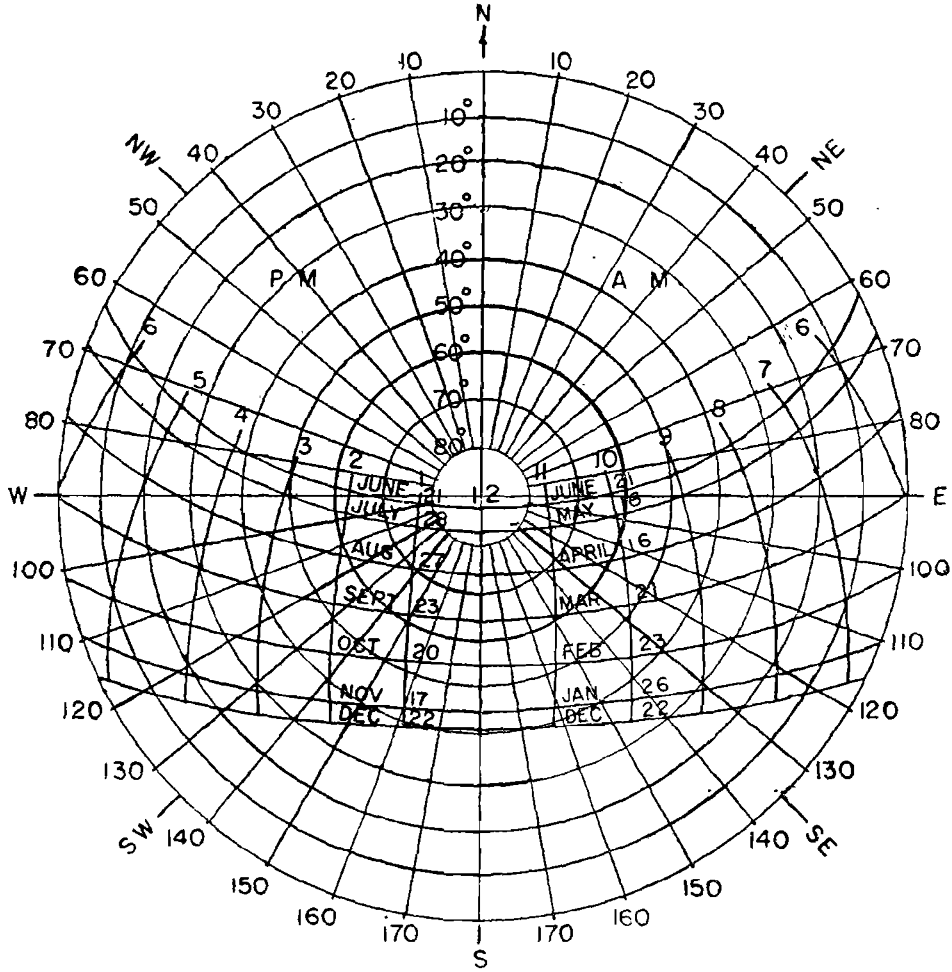

Fig. 1. Solar chart for Jodhpur

be seen that the intensity is higher during winter than during summer for the same optical air mass. It may also be seen here that when the sun is sufficiently high in the sky or during the period from 10 a.m. to about 3 p.m., more than one cal/cm² min. is received, and this is a sufficiently high amount of energy for focussing collectors. These figures clearly indicate the possibilities of a large-scale use of appliances for utilizing solar energy in the arid and semi-arid regions of our country.

SOLAR WATER-HEATER

Solar water-heaters may be divided into two main types and several variations of each exist. Both utilize the flat-plate principle, whereby solar energy is absorbed by the water being heated. No concentration or focussing is employed in the systems now in practical use. The primary distinction between the two types is that one comprises separate solar-heating and water-storage facilities, whereas the other combines the heating and storage functions in a single unit.

The combined collector-and-storage-type solar water-heater. In this solar water-heater, the flat-plate collector performs the dual function of absorbing the solar heat and storing the heated water. A simple collector-cum-storage-type solar water-heater, with optimized configuration was first developed by Garg *et al.* (1972) in India and has since been extensively tested by him, first at Roorkee, and then at Jodhpur, with some modifications. The advantages of this solar water-heater are that it is cheap, operates at a high efficiency rating, reaching up to 70% and is easy to install and operate, the only disadvantage being that it does not ordinarily provide hot water for use in the early morning. For this purpose, the system has been modified by Garg (1975) by incorporating a reflector-cum-insulation cover for use during night. Another alternative would be to drain the hot water produced during the day into a separate insulated drum in the evening and store it for use in the early morning.

This combined collector-cum-storage-type solar water-heater consists of a rectangular, 20-guage, galvanized-iron tank, with an optimized configuration, measuring 112 × 80 × 10 cm, with a capacity of 90 litres. It is contained in a box of mild-steel sheet, with a 5-cm layer of fibreglass insulation on the rear as well as on the four sides and with one colourless glass (3 mm thick) cover at the top. The bulging of the tank under water pressure is reduced by using angle-iron flats bolted on the sides of the box. The front face of the tank is blackened with lamp-black paint. This absorber-cum-tank performs the dual function of absorbing the heat and storing the heated water. The main water-supply line is connected through a gate valve to the inlet pipe (12 mm in diameter) fixed at the bottom of the tank. A vent pipe is also provided for safety purposes. The heater is of the non-pressure type and works on the push-through principle. Hot water can be taken out from the heater by opening the gate valve provided on the inlet side of the heater. The heater is inclined at 41 degrees from the horizontal and is orientated due south to collect the maximum solar radiation during winter at Jodhpur (latitude 26.30 deg. N).

For rural use, where there is no mains for water-supply, a bucket is fixed at the top of the heater and its lower end is connected to the inlet pipe of the heater through a piece of flexible plastic hosepipe. Hot water can be taken out immediately by putting the same amount of cold water in the bucket. In order to obtain hot water early in the morning, a hinged aluminium reflector-cum-insulation

Table 3. The monthly means of maximum water temperature (°C) reached in the low-cost solar water-heaters, along with the monthly means of the daily total solar radiation (cal/cm/day) on a horizontal surface at Jodhpur during 1973–75

Months	1973		1974		1975	
	Water temp.	Solar radiation	Water temp.	Solar radiation	Water temp.	Solar radiation
January	53·7	369	60·9	395	58·0	353
February	60·2	429	61·4	455	61·5	428
March	63·9	483	64·6	499	64·6	533
April	66·3	550	63·3	517	64·5	557
May	66·4	520	64·4	638	63·2	559
June	56·2	397	59·7	558	61·4	615
July	54·8	425	58·8	448	52·6	514
August	54·0	325	64·2	470	55·0	434
September	63·0	409	75·1	475	52·8	351
October	70·8	459	74·1	452	59·7	435
November	68·4	366	72·5	398	62·3	385
December	59·3	343	61·5	343	60·0	372

cover has been fixed to this heater (Garg, 1976). This cover has a 5-cm fibreglass insulation and an aluminium reflector, facing the glass of the heater. The insulation cover can easily be put on the heater like a lid of the box.

Data on the monthly means of maximum water temperature reached in the water-heater, recorded at 4 p.m., alongwith the total solar radiation on a horizontal surface, are shown in Table 3. It is evident from this Table that in winter, the maximum attainable temperature of the water would be 50° to 60°C, whereas in summer and the monsoon (except on a few rainy days), water at a temperature from 50° to 75°C can be obtained.

As this water-heater works on the principle of the push-through system, the temperature of water goes on decreasing as one goes on drawing hot water from the gadget. The performance of this type of water-heaters during winter has been observed and the data are presented in Table 4.

It has been observed that as the depth of the storage tank increases, the collection efficiency increases, since the thermal losses of the outside air decreases. From the efficiency curve, it can be seen that up to a depth of 10 cm, the rise in efficiency is very fast, but after that there is a negligible rise in efficiency. Thus it is concluded that a depth of 10 cm gives the optimum performance.

Natural circulation-type domestic solar water-heaters. In this type of solar water-heaters, the storage tank and absorbers are separate and the water gets circulated through the thermosyphon action. Here, generally, the tube-in-plate type of collectors are employed. The efficiency of this type of collectors depends on a number of design parameters, such as the tube material and its diameter, the spacing between tubes, the plate material and its thickness and bond conductance. The following combination of materials and dimensions has given the minimum cost per unit of efficiency.

G.I. tube diameter	10 mm
Plate material	Aluminium
Thickness of plate	28 SWG
Tube spacing	10 cm

Once the configuration of the collector has been optimized, it can be made in any size, depending on the requirement. A few characteristics of this type of collectors have been shown in Fig. 2. This figure can be used for designing.

SOLAR DRYING

Since the dawn of history, solar energy has been used for open air-drying of a number of agricultural products, such as hay, cereals, fruits, vegetables, timber

Table 4. The effect of insulation cover on the water temperature (°C in the improved solar water-heater in winter at Jodhpur during 1973–75)

Month and year	Without insulation cover at night		With insulation cover at night		Tap-water temperature at
	4 p.m.	8 a.m. (next day)	4 p.m.	8 p.m.	8 a.m. (°C)
Jan. 1973	48·3	18·5	48·6	33·0	16·2
Feb. 1973	52·2	21·3	51·5	33·8	17·3
Nov. 1973	53·3	24·5	54·1	34·5	23·1
Dec. 1973	52·1	21·8	53·0	33·5	19·4
Jan. 1974	51·6	21·2	50·2	33·9	17·0
Feb. 1974	52·5	22·6	51·3	32·3	17·5
Nov. 1974	58·3	26·3	57·2	41·3	24·2
Dec. 1974	53·1	20·0	53·3	35·5	16·8
Jan. 1975	47·6	18·8	48·2	30·9	15·9
Feb. 1975	49·6	19·6	50·1	32·5	16·3
Nov. 1975	54·6	25·5	53·2	37·0	23·2
Dec. 1975	51·5	21·3	50·4	31·8	19·5

and fish, and non-agricultural products, such as bricks, the retrieving of salt from the sea-water, rubber sheets and paper. In these free natural sun-drying processes, usually the high labour cost, the inferior quality due to contamination by dirt and insects, the degradation of the products,

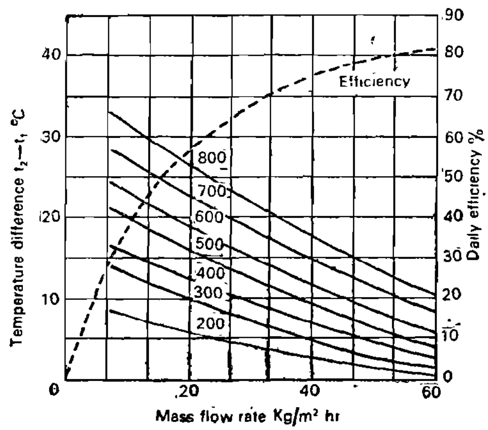

Fig. 2. Design curves for natural circulation type solar water heater with optimized collector configuration

wastages, etc. are frequently encountered. In India, only 0.5% of the 32 million tonnes of fruits and vegetables produced every year is processed and preserved by the industries and about 25% of the total production gets spoiled before it reaches the consumers. Similarly, a considerable amount of farm produce, e.g. wheat and paddy, is spoiled because of high humidity at the time of storing. Therefore the need for adopting moderately controlled methods, such as mechanical drying with heated air or steam, have become apparent in recent times, since such methods are independent of weather conditions and give rise to good-quality products. The high cost of operating mechanical dryers make the end-products so expensive as to make it imperative to search for cheaper means.

With the application of minor technology and at a relatively little cost, sun-drying may be made an efficient process.

Solar dryers are broadly of two types. In the direct drying in solar dryers, the material is directly exposed to solar radiation in a hot box-like arrangement and because of the absorption of solar energy and air circulation, the moisture gets vaporized. These dryers are very suitable for drying different products. In the indirect type of solar dryers, generally known as the forced-circulation-type dryers, the material is kept in a separate drying-unit in some convenient place, and the air heated by passing through solar air-heaters, dries the material. These dryers can be used for drying large quantities of produce and can also be used in industries.

CABINET DRYERS FOR FRUITS AND VEGETABLES

In India small cabinet dryers for drying fruits and vegetables have been developed at the CAZRI, Jodhpur, at the I.I.T., Kanpur, and at the Annamalai University, Tamil Nadu. A number of trials for the dehydration of chillies and *ber* (fruit of *Zizyphus nummularia*) and for converting grapes into raisins have been conducted at the Central Arid Zone Research Institute, Jodhpur. The Forest Research Institue, Dehra Dun, has developed a solar timber-seasoning kiln which cuts off 40% of the time required for seasoning. Forced convection-type dryers are presently being developed in the country at the CAZRI, Jodhpur, at the IARI, New Delhi, at the I.I.T., Kharagpur and at the Annamalai University, Tamil Nadu.

The dryer consists of a rectangular wooden box made of wooden planks (25 mm thick) with a basal area of 1.5 m^2. The bottom of the dryer is insulated with a 5-cm-thick sawdust insulation and a glass cover at the top at an angle of 23 degrees from the horizontal to receive the maximum solar radiation throughout the year. The inside walls and the base of the dryer are painted black and the drying material can be placed on perforated trays through a door provided on the back side. A number of holes are provided at the bottom and on the sides for the movement of air. The inside air temperature varies from 50°C to 95°C. With the help of this dryer, 15 kg of dates can be dehydrated and 15 kg of grapes can be converted into raisins within 2 to 4 days at Jodhpur, even during the monsoon season. Practically all types of fruits and vegetables can be dehydrated with this dryer.

SOLAR DESALINATION

Solar distillation is simple in technology and is full of promise for areas where potable water is not available for drinking. Moreover, distilled water is required in laboratories, petrol pumps, and health centres. In isolated places and salt farms, solar stills should be very useful. In some areas in the deserts, the salinity level of the available underground water may vary from 5,000 to 10,000 ppm, too high for drinking. The only source of drinking-water in these villages is the rain-water collected in 'tankas'. In view of this difficult situation, solar distillation would seem to have much scope in the arid zone.

The effects of different design variables as depth and cover angles and also of indigenous building materials on the output of distilled water have been studied at the CAZRI, Jodhpur. Their designs are available in the published literature or can be obtained from the National Research Development Corporation of India.

Work on solar distillation at the Central Arid Zone Research Institute, Jodhpur, has been mainly concerned with the specific aim of optimizing the size for a domestic solar still under the Indian arid-zone conditions. As a result, a number of single-sloped and double-sloped solar stills, both on the ground, with and without ground insulation, and on raised platforms have been fabricated and an hourly record of distilled-water output has been maintained for two years and a half. The effect on the output of distilled water of a number of climatic parameters, such as solar radiation, ambient air temperature, outside wind speed, outside air humidity, and design parameters, such as base insulation, coverglass inclination, orientation of still-single-sloped and double-sloped, and operational parameters, such as the depth of water in the basin, the preheating of water, the colouring of water, have been experimentally studied at the CAZRI. Now efforts are being made to optimize the size of the solar still for domestic use as well as for laboratory use.

SOLAR COOKING

According to a recent report published by the United Nations Environment Programme (UNEP), there is shortage of firewood for every third person in the world. Besides advocating mass tree-planting schemes, the report underlines the importance of developing alternative cooking devices, such as the solar and the biogas cookers.

In rural India, about 95% of the fuel requirement is met from firewood, dung-cakes and vegetable wastes, of which firewood constitutes the major share of 58.6%.

There can be little doubt that the agricultural sector will benefit immensely, if cowdung and agriculture wastes are used as organic manure instead of burning them at an efficiency of only 10%. Solar energy, if harnessed economically through cheap solar cookers, may provide a ready alternative source of supply of domestic fuel for cooking. Although the technical aspects of the development of a solar cooker are simple enough, its advantages become significant only when the solar cookers are used extensively.

Recently, a systematic techno-economic study of the development and field performance of different types of solar cookers has been undertaken at the Central Arid Zone Research Institute, and on the basis of this study, five different types of solar cookers or ovens have been designed and fabricated and tested in the laboratory. The most efficient of these ovens consists of four square and four triangular plane-glass reflectors, along with a well-insulated semi-cylindrical box on the back side, made of sheet aluminium and wood, on the angle-iron stand for adjusting the oven towards the sun (Plate p). A cradle-like cooking-platform is made in the oven. It helps to keep the vessel containing the food materials to be cooked in the horizontal position, irrespective of the inclination of oven. The maximum temperature in the solar oven with the looking-glass reflector reaches up to 350°C in summer and 250°C in winter. Some of the cooking tests conducted on this oven are listed in Table 5.

Table 5. Cooking trials in a solar oven conducted at the Central Arid Zone Research Institute, Jodhpur

Type of food	Cooking time (minutes)
1. *Cooking*	
(a) Rice (1 kg in water)	45
(b) Potatoes (1 kg in water)	50
(c) *Arhar dal* (1 kg in water)	75
(d) Other vegetables (1 kg in water)	60
2. *Roasting*	
(a) Potatoes (1 kg)	60
(b) Chicken (1·5 kg)	60
(c) Fish (1 kg)	20
3. *Baking*	
(a) Cake (1 kg)	50
4. *Boiling*	
(a) Tea (4 cups)	25
(b) Milk (1 litre)	45
(c) Water (1 litre)	45

The performance of this oven is not affected by the wind; there are no chances of dust falling into the cooking-pot; the food remains warm for hours together after sunset, if kept inside the oven and this oven does not require frequent adjustments towards the sun.

SOLAR PUMP

To increase agricultural production and also the income per head, it is very necessary to increase the energy supply in the rural areas of the country. To attain a production level of 2,000 kg per hectare per head energy at an intake level of 3,000 food calories a day, 0.75 horse-power of energy would be required per hectare against the present availability of 0.35 horse-power. The major ingredients of an agricultural system are: soil, sunlight, water plants and animals. We are rich in all these ingredients, but ours is one of the least productive farming systems because of the inadequate availability of energy in the rural areas. There is a vast scope for multiple- and relay-cropping, provided more power is available for lifting water from wells and other sources, which are underutilized at present.

The development of a small solar pump of 2 to 5 kw capacity for irrigation can result in an agricultural revolution. In most of the arid areas and in some parts of the semi-arid areas, the major portion of our agricultural land is rainfed and if a portion of this land can be brought under irrigation, crop production can be substantially increased. As the power requirements for this purpose are localized in small scattered units, small self-sustained energy units would be very useful for this purpose.

From the operational point of view also, solar pumps are likely to prove more efficient and provide more years of trouble-free service than the conventional motors.

Solar pumps can be energized either by converting solar energy into electricity directly by solar cells or by converting solar energy into mechanical energy. The solar pumps based on the direct conversion of solar energy into electricity, using solar cells, are highly uneconomical at the present stage of technology. The solar pumps based on the principle of converting solar energy into mechnical energy are not only feasible, but have already been tried in France, the USA, the USSR and Israel. There is no reason for such devices not being put to use in our desert region. If simple, efficient and low-pressure-vapour engines or vapour turbines are developed, they can be used for converting solar energy into mechanical energy and finally water can be pumped by using centrifugal pumps, or with the reciprocating type of pumps. Even then, the capital and maintenance costs are likely to remain higher than those of the conventional types of pumps.

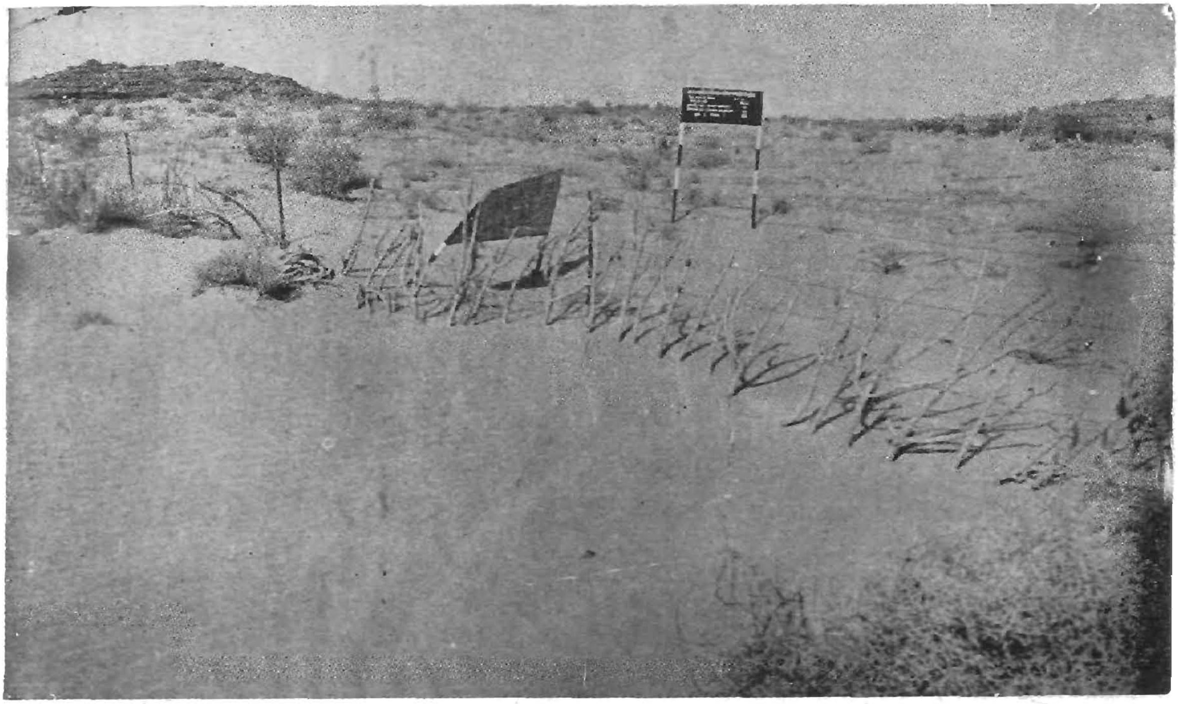

Plate r. A picture of sand-dune before initiation of its stabilization in ORP area

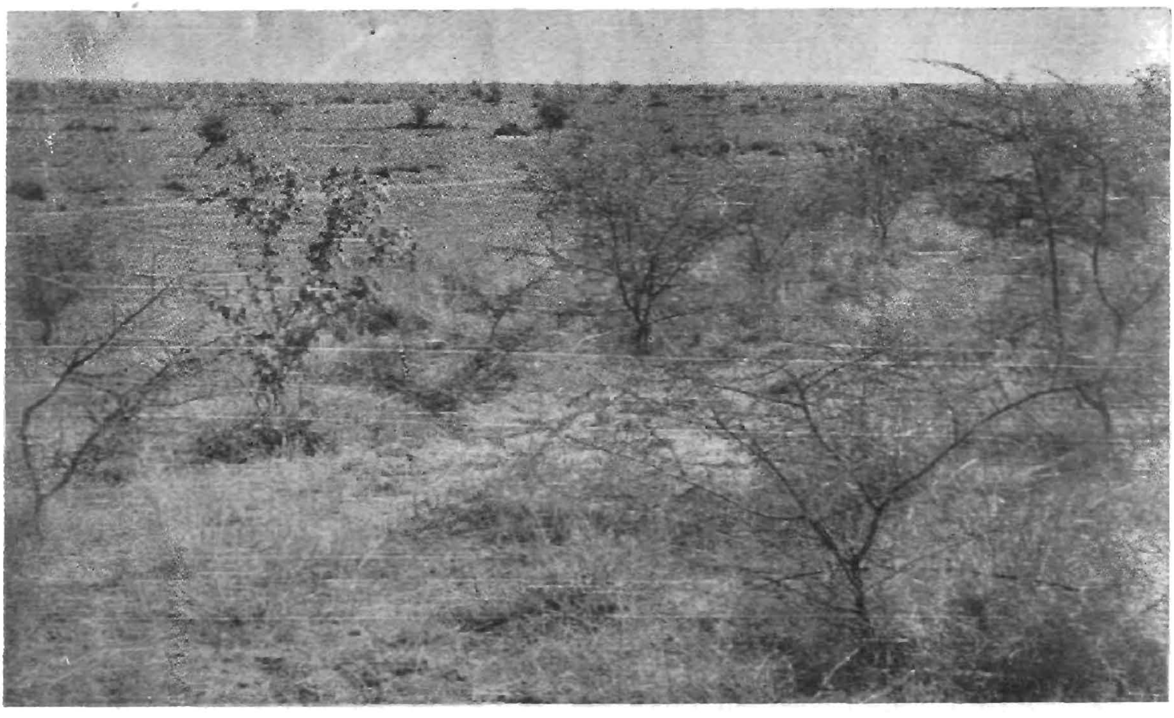

Plate s. *Acacia tortilis* trees flourish on the barren sand-dunes after their stabilization

Plate t. Lest the howling winds blow away the top soil — a soil conservation measure in practice

In a new type of low-cost pump, now being developed at the CAZRI, a number of flat-plate-bond-duct type collectors made out of aluminium sheets are used. The efficiency of these collectors is much higher than that of the collectors used in other solar pumps. An organic liquid with a low boiling-point e.g. ether, is passed through these collectors to give a very high vapour pressure. The vapours at a high pressure operate a diaphragm pump. The condensation and vaporization of the liquid makes the diaphragm to move backwards and forwards. This movement of the diaphragm is utilized for pumping water. This is suitable for pumping water even against high heads, is almost free from vibration and needs but little maintenance. Flat-plate collectors and a diaphragm pump which can operate at a low pressure has already been fabricated and tested by the author for their performances. A pump of this type, with no moving parts and with less of heat-exchangers, has been fabricated at the CAZRI and it is expected that the overall efficiency of this pump would be higher and the capital and running costs will be lower than those of other types of solar pumps.

RURAL LIGHTING

Solar energy has great potentiality for running rural electrification systems in our country. The direct conversion of solar energy into electricity by using semi-conductor photovoltaic cells, or 'solar cells' as they are commonly known, is receiving worldwide attention now. The solar cells used for space applications are of extremely high quality and, therefore, the cost of these cells is about Rs 1,000 per watt. For terrestrial applications, such high-quality cells are not required. Moreover, a widespread use of these cells can only be examined, if the cost per watt is reduced at least by 100 times and the cells are made resistant to wind, dust, rain, humidity, etc.

In India, work on solar cells was started at the Indian Institute of Technology, New Delhi, in 1965 and at the Solid-State Physics Laboratory, New Delhi, in 1966 and both the institutions have developed solar cells with efficiency ratings reaching up to 10%. The cost of these cells is, however, very high. Obviously, much further study in depth is required in this field. Recently, the Department of Science and Technology of India has established the the Central Electronics Limited, which will do R & D work on solar cells and which will also co-ordinate research in this field. According to an estimate, by 1985, three million rural families in India will be able to generate their own electricity for lighting and for running their radios, using solar cells. The major technological effort should now be directed towards the development of materials, techniques and processes for large-scale, low-cost production of solar cells. Attention all over the world is concentrated on this goal and it is not unlikely that by the turn of the century, we will have solar-cell power-stations even in the remotest areas of our desert.

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SOCIO-DEMOGRAPHIC FACTORS AND NOMADISM IN THE ARID ZONE

S. P. MALHOTRA

SINCE the late fifties, the global view of population problem has been in focus in the deliberations of various international organisations. The present rate of population growth in the developing countries is penalizing hundreds of millions who live on the margin of subsistence. India is also faced with frightful population prospects, as the increase in population is more than 35,000 a day and has serious consequences on our national resources. Examined in the context of the Indian arid zone, it has been observed that the rate of growth of population in the region is relatively high and the dual increase in population and its needs set up an alarming situation, specifically when viewed in the context of extremely limited potentialities for agricultural and industrial developments in the arid areas. The arid areas of Rajasthan after Independence and at the time of the merger of the state into the Indian Union inherited a poor and undiversified economy, crippled through decades of neglect and feudal exploitation. For the purpose of the present discussion of socio-demographic factors in the arid zone of Rajasthan, a part of the State of Rajasthan lying west of the Aravallis, covering 2,13,800 km^2 and constituting 12 districts, namely Jaisalmer, Jalore, Jodhpur, Pali, Barmer, Churu, Sirohi, Bikaner, Ganganagar, Nagaur, Sikar and Jhunjhunu, has been considered. An attempt has been made to describe the population density and spatial distribution, major population trends, the growth potential, growth factors, the implications of population growth in the region and the policy options. A proportion of the population is nomadic and forms an important problem in the Indian arid zone. Their way of life and rehabilitation measures have also been discussed.

Population density and spatial distribution

By the arid-zone standards, the Rajasthan desert is one of the most thickly populated deserts of the world, and has an average density of 48 persons per km^2, as compared with 3 persons per km^2 in most other desert regions of the world. Though the variations in the densities of population do occur on account of topography, soils, land, the occurrence of economic minerals, accessibility and other socio-economic factors, water is the most important factor determining the distribution and density of population in the arid zone of Rajasthan, where agriculture is predominant and mining is still undeveloped. The coefficient of correlation between the rainfall and the density of population in the arid zone of Rajasthan was worked out at +0.6079, which is positively significant, whereas the values of 'r' exhibited a negative correlation between the population density and the average annual rainfall in the plain ($r = -0.2923$) as well as in the hilly regions ($r = -0.0172$) of Rajasthan. The population density in the District of Ganganagar is higher owing to the availability of surface water through canal irrigation. Similarly, the districts, such as Jhunjhunu, Nagaur, Jodhpur, Sikar and Pali, having greater facilities of well and

Table 1. Sex-wise rural and urban growth of population in millions

Year/population growth rate	Rural			Urban			Total population		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
1901	1·599 —	1·416 —	3·015 —	0·279 —	0 274 —	0·553 —	1·878 —	1·690 —	3·568 —
1911	1·752 (+9·56)	1 563 (+10·42)	3 315 (+9 96)	0 284 (+1·76)	0·279 (+1·84)	0·563 (+1·80)	2·036 (+2·97)	1·842 (+15·07)	3 878 (+8·70)
1921	1·596 (—8 88)	1·409 (—9·83)	3 005 (—9·33)	0 292 (+3·04)	0·278 (—0·62)	0·570 (—1 23)	1·888 (—2·33)	1 687 (—13·24)	3·575 (—7·80)
1931	1·886 (+18·15)	1 686 (+19·65)	3·572 (+18·85)	0 368 (+25 93)	0 344 (+23·75)	0·712 (+24 87)	2·254 (+10·36)	2 030 (+20·32)	4 284 (+19·81)
1941	2 301 (+21·98)	2 053 (+21 75)	4·354 (+21·86)	0 484 (+31·64)	0·438 +27·54)	0·922 (+29 66)	2 785 (+23·56)	2·491 (+22·72)	5·276 (+23 16)
1951	2·568 (+11·64)	2 3345 (+14 23)	4 913 (+12 86)	0 639 (+31·87)	0 607 (+38·38)	1·246 (+34 96)	3·207 (+15 16)	2·952 (+18·48)	6·159 (+16·73)
1961	3 437 (+33 79)	3 145 (+34 10)	6·582 (+33 94)	0·743 (+16·38)	0 672 (+10 78)	1·415 (+13·65)	4·180 (+30·31)	3 817 (+29·31)	7·997 (+29·84)
1971	4·332 (+26·05)	4 017 (+27·74)	8·349 (+26·86)	0·970 (+30·46)	0·913 (+35·82)	1·883 (+33·01)	5 302 (+26·84)	4 930 (+29·17)	10 232 (+27·95)
Overall change	+170·89	+183·74	+176·94	+248 06	+232·58	+240 38	+182·35	+191·70	+186·78

tank irrigation show a higher density of population. The density of population declines from the foothills of the Aravallis to the narrow belt between the Sutlej and the dry bed of the Ghaggar and the thirsty sands of the desert. The density of population per km² in Jhunjhunu is 157 persons; in Sikar, 135; in Pali, 78; in Nagaur, 71 and in Jalore, 63. Proceeding towards the west, the density per km² decreases fairly rapidly, with 52 persons in Churu, 50 in Jodhpur, 27 in Barmer, 21 in Bikaner and only 4 in Jaisalmer.

The pressure of population may best be studied by comparing the total population and the total sown area (the net sown area + the double-cropped area) in the different arid districts. As shown in Fig. 1, the number of persons per km² of the sown area (physiological density) is the lowest (61) in the District of Barmer which has an average annual rainfall of 277 mm.

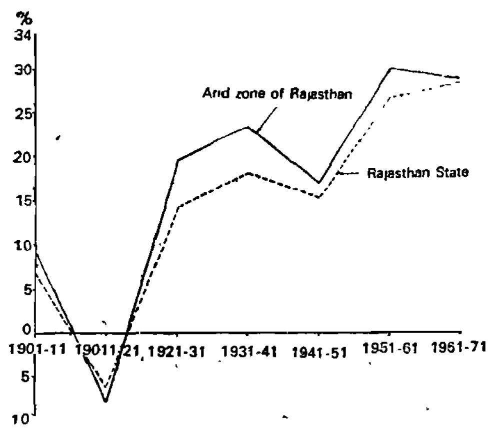

Fig. 1. Annual growth rate of population in different census periods

As the rainfall decreases below this figure, the physiological density increases, e.g. in Jaisalmer (rainfall, 164 mm; population density, 110). Bikaner (263.7 mm, 89) and Ganganagar (253.7 mm, 95). On the other hand, where the rainfall increases above this figure, the density also increases, i. e. Churu (325 mm, 70), Jalore (421.6 mm, 83), Jhunjhunu (444.5 mm, 184), Jodhpur (318.7 mm, 97); Nagaur (388.6 mm, 101), Pali (490.4 mm, 154), Sikar (441.4 mm, 179), and Sirohi (638.4 mm, 225). The higher physiological densities in the wetter districts are due mainly to intensive cultivation, whereas they are higher in the drier districts mainly because of the increases in pastoral activities.

Major population trends

As shown in Table 1, starting with a base of roughly 3.567 millions in 1901, the population in the arid zone of Rajasthan registered a linear escalation and increased to 10.236 millions, i. e. the population of the region registered an increase of over three times its size in 1901. Whereas the overall growth rate of population during 1901-1971 had been of the order of 186.78 %(males+182.35% and females+191.70%) the rural population increased by 176.94% (males+170.89 and female+183.78) and the urban population increased by 240.38% (males+248.06% and females+232.58%). The higher urban growth rate as well as the higher growth rate of the male population in the urban areas is attributable to the migration (more of the male population) from the rural to the urban areas for livelihood. Meanwhile, as shown in Fig. 1, it is observed that during each successive decade (except 1911-1921), the population showed a constant increase, indicating thereby that each successive, generation had been more numerous than the preceding one. It is further interesting to note that the percentage increase of population during each decade had been higher in the arid zone of Rajasthan than in the Rajasthan State as a whole. As against 186 %, the growth rate of population (1901-1971) in the arid zone of Rajasthan, the Rajasthan State, as a whole registered 150% increase and the increase in the country during the period has been of the order of 132%. These figures evidently reveal that the growth rate of population in the arid zone of Rajasthan has been higher. Even, when the growth figures for the Ganganagar District (where immigration had been high) are not included, it was found that the rate of population growth was still higher in the arid zone of Rajasthan (158%).

The enormous acceleration of growth in recent times is shown by the fact that the number of new additions in only ten years (1961-71) was worked out at 62.64% of the number present at the beginning of the century. The relatively small growth rate of population in the decade 1901-10 and the decline in population in the next decade is most likely due to heavy mortality during the period. In recent years, the development of the means of communication and the extension of medical facilities have considerably reduced the number of deaths. Thus a much higher percentage increase *in population in the arid* tracts of Rajasthan poses an alarming situation, specifically when viewed in the context of limited resource potentials of the region.

Growth potential

The future potentialities of the growth of population are indicated by the present age and the sex composition of the population and its marital status. The age and sex composition (Fig. 2) of the population of the arid zone of Rajasthan reveals a *pyramid with a broad base and represents* a preponderance of the young population e.g. those under 10 years of age represent 31.39 per cent of the total female population and 31.57 per cent of the total male population. The percentage distribution of children (0-14 years), young (15-34 years), middle-aged (35-54 years) and old (55 years and above) worked out at 43.75, 28.18, 17.20 and 7.26 respectively during 1961 and 43.35, 29.75, 17.38 and 7.52 respectively during 1971. It is thus observed that the younger people (0-34 years) constitute over 75% of the total population that would substantially enhance the population in the near future even if measures are taken to check the population growth. Taking the population within the age-range of 15-54 years as productive it is found that 47.12% of the population in the productive ages works for 52.88% of the population in the non-productive ages, i. e. every 100 persons in the productive age-group work to support 112 persons in the non-productive ages. This high dependency, unbacked by the adoption of competent and relevant improved production technologies, thus, presents a *dismal picture.*

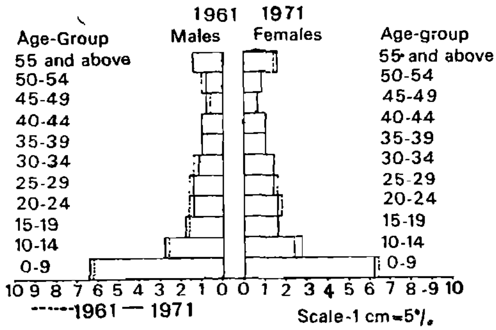

Fig. 2. Age and sex composition of population inhabiting the arid zone of Rajasthan

Marriage is another important variable connected with age and sex, which is indicative of the future growth of the population. Marriages in respect of both sexes in the arid areas show a rather interesting pattern. The age distribution of unmarried males and females in 1951, 1961 and

Table 2. Age and sex distribution of the unmarried population in the arid zone of Rajasthan

Age-group in years	1951		1961		1971	
	Male %	Female %	Male %	Female %	Male %	Female %
0-14	78.20	93.70	79 57	96·15	79·33	94·82
15-34	18.40	5·70	18 28	3·57	18·75	5 11
35-54	2.30	0.40	1.40	0·09	1·39	0 04
55 and above	1.10	0·20	0·75	0.19	0 53	0·03

1971 (Table 2) reveal the practice of early marriage.

The data indicate that there are very few unmarried people over 35 years of age, showing a universal nature of marriage. Even in the age-group 15–34 years, the percentage of unmarried women is very small. Indications of the future growth rate of the population are further available by analysing the figures relating to the number of females in the reproductive period (15–44). There are 4,037 females in the age-group 15–44 years for every 10,000 women of all ages, and this number is quite high. The age composition of the females (Table 3) in the reproductive period and their marital status further indicate the expansive potentialities of the future growth of population. It is observed that there are a large number of women in their first half of the reproductive period all through 1951–1971 than in the second half of the reproductive period. Further, the percentage of married women in the reproductive period was worked out at 90.31, which is also indicative of the civil condition of the female population predisposed to very high growth rate.

Table 3. Distribution of women (five-year age-group) in the reproductive period in the arid areas of Rajasthan

Age-group in years	1951	1961	1971
15–19	19 10	18 39	20 01
20–24	18·40	21 72	19·84
25–29	19·60	19·44	18 03
30–34	17·70	16 64	16·85
35–39	12 20	11 45	12 66
40–44	12 90	12 36	12·61

One may surmise that if the growth of population remains unabated and the rate of growth remains the same as during the decade 1961–1971, by the turn of the century the population of the region will be over 21.54 millions which is much more than the present population of the continent of Australia. In fourteen decades it will match the present population of the country. It is, no doubt, evident that the population checks would definitely come up, but such wild guesses are only a warning against the future population pressure and a hint at the nature and extent of societal efforts necessary to avert the population explosion.

Growth factors

In spite of the dearth of reliable vital statistics, the impact of rapidly declining mortality is obvious. The major factor responsible for such a phenomenal rate of growth of population is the widening gap between the birth and the death rates. By and large, the external migration has played a relatively insignificant role in the population dynamics of the arid zone. Immigration has been very limited in the arid areas because of the absence of the factors like productive lands, large-scale industries and mineral production. In spite of the heavy push factors, viz. overcrowding on the already oversaturated lands, etc. there has not been much of outmigration mainly because of the lack of pull factors (like absorption in big industries or other urban vocations) and also because of the backwardness of the people, poor means of communication and the sway of the social institutions, such as the joint-family system, caste-system, early marriage, and the illiteracy and conservatism of the people. For instance, the percentage of immigration from other States to Rajasthan (1961 Census) has worked out at 4.90% of the total population, whereas that of outmigration from Rajasthan to other States was worked out at 5.62%. Thus the net outmigration was worked out at 0.72% of its total population. The immigration in the arid zone of Rajasthan had been further low and was worked out at 2.14% of the total population. Of this, the district of Ganganagar claimed 70.74% of the inmigrants, and the other eleven districts did not attract immigrants, as the social inertia for it is quite limited. The increase in population may, therefore, be attributed mainly to the widening gap between the birth rate and the death rate. The chief factor responsible for the future growth potential of the population are the social values predisposed for having more children. Positive sanctions for fertility far outnumber the negative ones. Early marriage and the begetting of children are important parts of the social ethos of these people. Mainly, to save expenditure on separate feastings, marriages of the girls of lineage in which a person has died are performed on the third day of his death when a death feast called 'mossar' is organized. Child marriages are most prevalent and the minimum age of marriage of both girls and boys may be even less than a month. The actual consummation of marriage (muklawa), however, takes place when the girl has attained the age of 12-14 years. Marriages once enacted cannot be annulled. Any deviation from the established norms being not only looked down upon as grossly aberrant but also as wholly incompatible with the social fabric of the community. Divorce is a rarity, if not altogether unknown, and widowhood soon culminates in remarriage. Improved medical care in recent times has greatly minimized mortality at birth and has increased longevity.

Additionally, more than eight out of every ten persons still live in the rural areas, with all their problems, backwardness and daily life saturated with customs and practices which often override prudence. Their percentage literacy and its level is rather low and even today, not even 2 out of every 10 persons are literates and the percentage of rural people possessing functional literacy is rather insignificant. The percentage literacy among the female population was worked out at 5.86 in 1961 and only 7.85 in 1971, thus exhibiting a very insignificant increase during a decade. Similarly, the rural females getting work outside the home (apart from the family labour that they provide) would have been another factor responsible for changing the attitude of the females for limiting the number of children that she should bear has not exhibited a substantial increase.

Most of the labour force (over 80% of the working population) is tied up to a pre-modern agriculture which suffers from an additional handicap of increasing scarcity of crop land. This major form of human occupation is marked by instability that carries the hazards of sudden failure, leading to famine conditions. Under such circumstances, to a person, who needs a fresh capital to be able to produce or earn, an extra child is a very good risk capital. And since many of these children do not go to school, the cost of this risk capital far outweighs the tempting benefits that this will provide right when the child attains 9-10 years of age. At this small age, the children are initiated as workers in desert areas, specifically engaging them in livestock-grazing, etc. Caste is still the pivotal social institution and has restricted social and occupational mobility and fostered values and sanction concerning fertility. Laden with socio-religious factors and values predisposed to having a larger number of children, the growth potential exhibited is quite high. The high growth rate of population coupled with the so-called modern impact has led to the break-up of the traditional joint families, with their deep ties in the rural community to the formation of the nuclear families. Of the households surveyed (Malhotra and Sen, 1964), 52% were found to be nuclear. With this transformation of the households, individualism has become increasingly manifest in family relationships. The disappearing of joint family is thus posing a paradox, just at the time when new longevity conditions are generating the necessity for the care of the aged in the joint family. The other forces are conspiring against it and more and more nuclear families are being formed. There being no State-mooted old-age security measures (old-age homes, old-age pensions, etc.), the parents like to have an additional number of male issues, so that they can fall back upon at least one during their old age.

Implications of population growth

During the feudal times, the population size was one of the very important factors to maintain power, prestige and labour force. Owing to changed circumstances, size *per se* is not critically as vital as it was in the past. On the other hand, when we see the impact of increasing density on the viability of the ecological unit, the negative effects of the increasing density on the socio-economic situation are not hard to find. For instance, the youthful-age structure, the high dependency ratio, primarily consisting of children and young adults, require much heavier outlays for simple maintenance, education and training for the future as well as for the fast multiplication of job prospects. It may be observed that the youthful population in the arid zone of Rajasthan grew at a much faster rate-nearly twice as fast as the growth rate of the total population, thus intensifying the difficulties in meeting the demands of the expanding youth cohort. The revolution and other forms of radicalism are associated with a preponderance of youth population (Weiner, 1971), and if the present faster growth rate of the youthful population continues, it may lead to the problem of a generation gap resulting in serious disruptions.

The economy of the arid zone of Rajasthan, based mainly on agriculture, has not been able to keep pace with the fast-growing population with the increase in the working force, there has been an overcrowding in agriculture, as the region lacks a diversified base. The situation is more revealing when we take the man-land ratio and the high proportion of labour force dependent on land. Fig. 3 represents the total land availability per household and also the different categories of land available per household in 1951, 1961 and 1971 and its estimated availability during 2001. It is observed that while the total land available per household was only 17.77 ha in 1951, only, 14.69 ha and 12.40 ha was available during 1961 and 1971 respectively and only 7.52 ha is likely to be available by the turn of the century. Similarly, the total cultivable land available per household declined from 13.72 ha to 9.95 ha in 1971, and only 6.03 ha is likely to be available in 2001. Studies conducted on the diffusion and adoption of improved technology by the rural population (Malhotra *et al.*, 1972) revealed that it had so far made only a small leeway and the fruits of improved technology had not been harvested to a significant extent by the farming population. As a consequence, more and more marginal lands are being brought under the plough, as is evident from the land-use statistics. The net sown area increased by 44.64% during 1951-61 and by an additional 9.47% during 1961-71 and the area under the less intensive uses of land (barren cultivable and uncultivable wastelands, permanent pastures and fallow lands) declined by 16.83% during 1951-61 and further by 6.95% during 1961-71. Thus during 1951-71, there had been a substantial increase in the sown area at the cost of grazing-lands because of the extension of cultivation to marginal lands. Paradoxical, as it may appear, on the other hand, the livestock population increased from 10.3 millions in 1951 to 14.5 millions in 1961 and to 16.4 millions in 1971.

One of the factors additionally responsible for using more and more of marginal lands for growing crops is the adoption of short-term welfare measures for the growing population rather than the use capability of land in the long run, e.g. the land-distribution policies in the region have aggravated the maladjustments in the land-use pattern. Most of land allotted to landless, marginal farmers, etc. was marginal and submarginal, and was added to the crop lands. As a consequence, the yield per unit of cultivated area is showing a declining trend. The annual linear growth rate (1954-70) worked out at −0.66, −4.88, −2.17, −6.08, −1.20 and 0.18 respectively for pearl-millet, sorghum, pulses, sesamum, gram and barley.

The rapidly growing population has inflated the demand for wood for different purposes, whereas it has reduced the area under fallows, wastelands and forests. All these factors indicate the trend towards an increasing scarcity of resources in the arid areas.

NOMADS AND NOMADISM

Additionally, a sizable proportion of the population leads nomadic or semi-nomadic

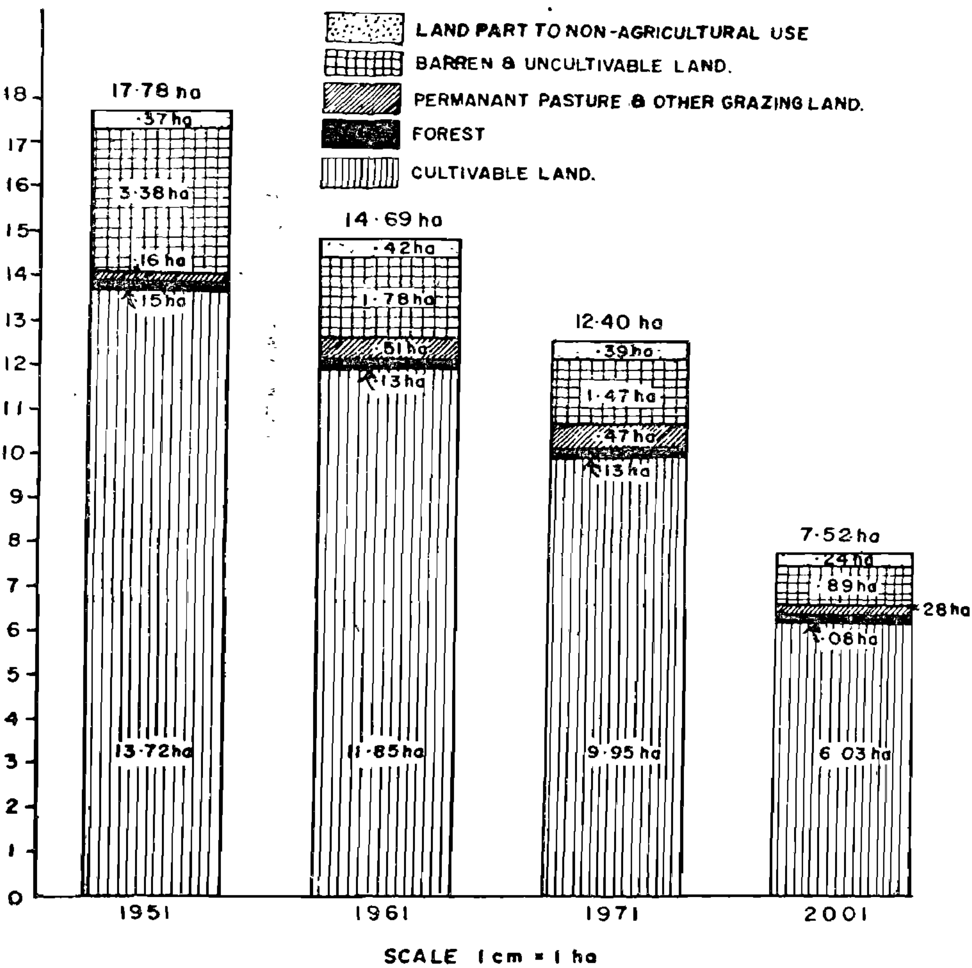

Fig. 3. Land available per household per hectare

life. The sources of livelihood and the way of life of the people have been conditioned by the disturbance in the ecological balance owing to the severity of the arid climate, the continuous deterioration of the soil, the dwindling of natural resources, occasional drought, invasions by outsiders, poor means of communication and consequential social and economic uncertainties. Famines of different kinds, namely *akal* (great famine), *jalkal* (scarcity of water), *tinkal* (scarcity of fodder) and *trikal* (scarcity of fodder, water and grain) have been of common occurrence in the region. To cope up with such unfriendly climatic and environmental conditions, the inhabitants have been resorting to nomadic and semi-nomadic life. They are not a separate ethnic group and do not have a separate territory, with exclusive rights and economic framework. The resource use being the decisive factor of the pattern of their living, the nomadic groups of the arid zone may be broadly grouped into four categories, viz. (a) the pastoral nomads (*Raikas, sindhis, barihars, billochs*, etc.),

(b) the trading nomads (*banjaras*, *ghattiwala jogis* and *gawarieas*), (c) artisan nomads (the *gadoliya lohars*, *sansis* and *sattias*), and (d) miscellaneous types of nomads (*nats*, *halbeliya jogis*) (Malhotra, 1971).

Relationship with settled population

Each type of nomads is associated with some kind of livestock which makes indiscriminate use of the meagre available water and grazing resources and destroy the local soil-conservation measures. The nomads in the present times, thus, are a menace to the whole society and their sedentarization is imperative. The opening up of the means of communication has reduced the importance of distribution activities by the trading nomads. The shrinkage of grazing-lands in some areas due to the extension of cultivation has created difficulties for the cattle-breeding nomads. Villagers are no longer dependent upon those nomads who once rendered specialized services. As shown in Fig. 4, it is evident that the sedentary population, in general, does not welcome the nomads to visit their areas.

It was thought that the settled population did not get any benefit from the pastoral nomads *sansis*, *sattias* and *nats*. About the visits of *banjaras*, two-thirds of the respondents felt that there was no benefit, whereas one-third of them felt that the settled population could purchase salt and other commodities from them. About the other trading nomads, a significantly greater percentage felt that the articles could be purchased, sold, exchanged or repaired.

Pastoral nomads

The pastoral people inhabiting the Rajasthan desert have been carrying on livestock-breeding for generations and have contributed to the economy of the region by way of providing milch cattle, *ghee*, wool, mutton, etc. A detailed survey (Malhotra *et al.*, 1966) conducted among the livestock-breeders of the Anupgarh-Pugal region revealed that these nomads had been facing difficulties in grazing their

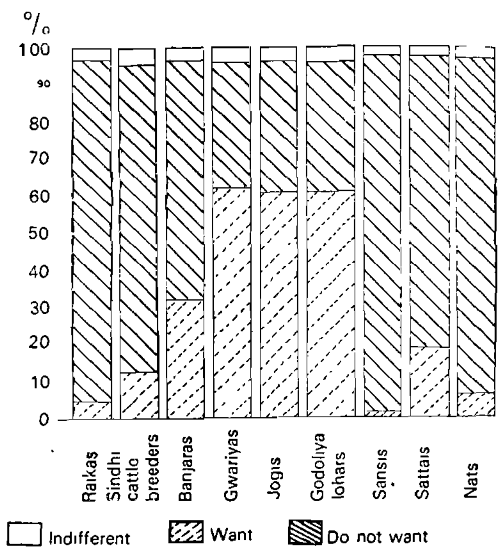

Fig. 4. Reaction of the inhabitants about the visit of nomads in Duni Basin.

livestock, as there had been a shrinkage in the extent of grazing-lands owing to the extension of cultivation and also with the coming in of the Rajasthan Canal to this area, the economy of these livestock-breeders is being much disturbed. The inhabitants of the region are not completely nomadic, but have permanent homes and generally have parcels of land. Their nomadism is directly dependent on the necessities of their herds. The economy of these breeders is largely dependent on the harvesting of the available water and the efficient use of extensive grazing-lands available in the area, as the cultivated area is only 4% of the total land surface.

Among the breeders, water-harvesting for livestock has been in vogue for generations. Having evolved a regional ecological association, the traditional livestock-breeders of the region are maintaining it more profitably and effectively for raising livestock in the region. This old method, presently known as *toba*, constructed amidst the sand-dunes, which provide water and pasturage for the livestock, is a very fascinating place to live in. A hard plot of land with very low porosity is searched for constructing the *toba* and again this place should form a good catchment area, so that water from all the four sides runs and collects at this place. Each village of the cattle-breeders has 5-6 *tobas* dug, depending upon the caste and community composition.

With the onset of the monsoon, there is a dispersal of herds far and wide within the boundaries of the village, wherever surface water is available in the dug-out *tobas* which are constructed and kept in repair for the efficient use of the meagre available water and grasses. The use of *tobas* is regulated by conventions and it is customary to make use of other *tobas* when the water in one's *toba* is exhausted. Nobody was thus prepared to deepen his *toba* lest the grazing resources are utilized by others. Thus the people stressed that the *tobas* had to be dug deep on a large scale rather than making any piecemeal efforts. In case the rains fail, the breeders migrate with their livestock to the irrigated areas of the Ganganagar and Ferozepur districts. Before the formation of Pakistan, they used to go up to the Bahawalpur region which is now a closed boundary.

It has been recommended (Malhotra *et al.*, 1966) that each household in the canal-commanded area may be allotted 6.3 ha of land and a partial mechanization of cultivation may be resorted to. Dairying may be introduced as an industry on scientific lines. Sheep-raising is the chief subsidiary occupation in the region. At present, the sheep-owners have to travel long distances and their nomadism can be arrested by upgrading the short grass rangelands by reseeding these pastures with grasses, e.g. *anjan* (*Cenchrus ciliaris*) and *dhaman* (*Cenchrus setigerus*). The introduction of the mutton industry, the setting up of wool-grading and shearing-centres shall further save a lot of their energy and fetch the breeders much higher income than they earn at present.

Artisan nomads

The second important category of nomads is constituted by those who specialize in certain trades, much-publicised *gadoliya lohars*, *sansis* and *sattias*. The *sattias* and the *sansis* carry on a limited trade in cattle and render veterinary services to the livestock of the villages on their routes. It is the nomads, like these, who are known for their immoral activities, illegal transactions and skill in *thieving* and who have created a resentment in the minds of the settled population against the hapless nomads. They are placed even by the nomads themselves in the lowest category of their social hierarchy.

The nomadic blacksmiths are locally called *gadoliya lohars*. They are one of the artisan nomads in the States of Rajasthan, Punjab and Madhya Pradesh. Their territorial extension is even in the semi-arid and humid environments. The traditional occupation of the *gadoliya lohars* is blacksmithy and trade in cattle. Their movements to different places are dependent upon the availability of blacksmithy work and prospects of trade in cattle. They have developed a symbiotic relationship with the sedentary farmers for supplying them with agricultural tools and implements. They also sell utensils for the farmers' households. These materials are supplied to the rural population on cash or exchange basis. The technology of manufacturing the tools, implements and utensils of iron is indigenous and it involves hard work, and a large amount of labour. Almost all the members of a family remain engaged in this occupation. On the average, a household earns about one thousand rupees annually from this occupation. Uncertainty of the availability of work and risk in earnings has created feelings of fraternity and mutual give-and-take in society. Unlike other nomadic groups, generally they do not take loans from the moneylenders. They are economically and culturally very backward. Their children are normally not sent to school, and as such, illiteracy is very common.

The nomads move about in small kinship bands in their bullock-carts with their families. The nature of movement of different bands of these artisan nomads follow a regular cycle on regular monthly intervals (Malhotra *et al.*, 1966). They owe their allegiance to a definite demarcated area. In one band, the number varies from one to twelve families. During movements, they split themselves into smaller constituents which group and regroup at different places, depending upon their social and economic needs. Their movements are limited only to those places which are connected by roads or tracks on which their bullock-carts can go. Owing to the recent changes in economic and political set-ups and, the increasing means of communication, the *gadoliya lohars* are not as welcome in the villages now as about 15 years ago. About one-fourth of the *gadoliya lohars* stated that there has been a definite decrease in their getting work of blacksmithy and in cattle trade in recent years. Ninety-five % of the household surveys, therefore, desired to abandon nomadic life and lead a sedentary or semi-sedentary life, leading finally to sedentarization.

Slow Sedentarization

Efforts have been made by the State Government of Rajasthan to sedentarize *gadoliya lohars* in colonies consisting of many households at one place, but such sedentarization has achieved only a partial success. Most of them desired to sedentarize in small kinship groups consisting mostly of agnatic (related on the fathers side) and matrimonial relations. They desired sedentarization in a scattered fashion at a central place within the present area of their movement, locally called by them Chokla (Malhotra *et al.*, 1966).

Such a settlement shall ensure that the continuation of their symbiotic relationship with the sedentary population, the provision of marketing facilities for the articles fabricated by them and shall also provide them with better prospects for being allotted suitable agricultural lands, which they are most desirous to get. Over and above, this social change shall also rule out the occurrence of any feuds which are likely when too many households of different clans are settled at one place.

Trading nomads

The third important category of nomads-designated as the trading nomads consist of the *banjaras*, *ghattiwala jogis* and *gawariyas*. The *gawariyas* mainly cater for the village women, selling beads, bangles and trinkets, and use the donkey as the transporting animal for a fixed area of movements. Like that of the *gawariyas*, the area of the *ghattiwala jogis*, who manufacture and trade in grinding-wheels and earthen smoking-pipes is also fixed. While some of these trading nomads are on the move perpetually, others lead a restricted settled life, taking to cultivation or working as daily-wage agricultural labourers during the cultivation season. After the season, they start peddling their age-old wares again.

The *banjaras* are one of the most publicized trading group of nomads. They are organised into a distinct class in different territories (Malhotra and Bose, 1967). Each clan is divided into smaller groups called *tandas*. In each *tanda*, there are six to twenty families. The doctrine of collective responsibility operates among the members of *tanda* (Malhotra and Bose, 1967). The families within the *tanda* are bound by the ties of kinship which give security to the members. The rights, obligations and expectancies towards one another are well established. The structure of the family is patriarchal. Early marriage is very common among them. Every *tanda* has a headman who commands respect from other members.

The main occupation of the *banjaras* is trading in salt. They roam from village to village with bullocks which carry goods and other material possession that are only a few and limited to the bare necessities of life. Even though nowadays, the salt trade is carried on by big wholesale traders with modern transport facilities, it remains the main source of sustenance of most of the families of the *banjaras*. The trade is carried on with the family labour force. The women render only minor assistance in economic pursuits (Plate q).

With the onset of rains, the *banjaras* move towards saline basins where salt is manufactured. After rains, grass and water are available en route for their animals. In addition to the salt trade, they sell Fuller's earth and onions in the remote villages of the desert tracts. These *banjaras* move towards the Gujarat State during the post-monsoon period. There, they get ready employment in the form of hauling of commodities, e.g. building materials and grains, by their bullocks.

The nomadic *banjaras* do not avail themselves of any community facility and have no social and cultural relationships with the settled population whom they meet only for trade purposes. There is some communication between the money-lenders and the *banjaras*, as the latter generally take loans from them for their trade.

The *banjaras* are economically backward and their standard of living is very poor. As a result of improved means of communication and the opening up of hitherto inaccessible areas to road transport, their traditional relationship of mutual dependence on the sedentary population has broken down. The *banjaras* find it difficult to sell their commodities with a good margin of profit as in the past. The shortage of grazing-land is another problem for them. Their earnings have sufficiently declined and several of them are in perpetual debt. For sedentarizing the trading nomads (*banjaras*), the *tanda* should be taken as one unit for settlement purposes in different villages. It shall be highly desirable to make use of the existing administrative machinery among the nomads rather than supersede it.

The fourth class consists of miscellaneous nomads, e.g. the *nats* and *halbeliya jogis*, who earn their livelihood by showing acrobatics, jugglery and snake-charming at village fairs and to roadside gatherings.

The technological, economic and political changes of the recent times are influencing the nomadic population in this region with such rapidity that they are facing a social decay. This influence is chaotic in so far as it is not based on balanced and well-conceived plans, and is not adaptable to the traditional nomadic way of life, and their aptitudes. The sedentarization of the nomadic way of life is a gradual and slow process. Though all-round development of the region may result in a spontaneous sedentarization of the nomads, there is a possibility of social as well as cultural annihilation of the nomads. The question that haunts the ecologists and sociologists today is how to absorb these people within the framework of modern living and make them useful members of society by exploiting their natural aptitudes.

Government efforts made in the past have proved to be of limited success because of the short-sighted policy and unscientific approach, which completely overlooked the social structures and existing institutions that could have gone a long way in keeping the nomads together. The experimental attempts of the State Government to rehabilitate the *gadoliya lohars* in Sojat, Khanpur, Barmer, Shiv, Beawar and Kishangarh are classic examples of random allotment of land and unfulfilled promises.

Policy options

In Sauvy's (1961) blunt phrasing, it is always a question, i.e. which of the four parameters will be set in motion, viz. death, emigration, economic level and birth.

The population policy calling for increased mortality (Duza, 1975) is unthinkable, as it would be culturally and ethically untenable. Further, as in the case of other South-Asian populations (Myrdal, 1972), the population in the arid areas of Rajasthan are destined to live "within the lands of their birth" mainly because of the lack of pull factors, preponderant illiteracy and the sway of other social institutions. The strong push factors, e.g. declining man-land ratio, coupled with the recurrent famines to drive out the population to the cities and towns within the outside of the arid zone to work sometimes as under-employed day labourers. A significant section of the population leads a semi-nomadic life, and others migrate during famines along with their livestock. All the same, such pastoral nomadism or migration for animal husbandry or other purposes is temporary and such migrations are not of any demographic significance. The third factor in Sauvy's scheme, involving an economic solution in the form of progress in production, cannot be ruled out, but owing to the lack of possibilities of technical miracles and limited resource potentials, the portents on this count are likely to weigh heavily on the promises.

The only alternative, therefore, left is the reduced fertility, leading to small family norms through family-planning efforts. However, the Family-Planning Programmes undertaken in the region after Independence have yet to make any impact in the region owing mainly to its inherent weakness in terms of the negligence of cultural variables which are mainly responsible for creating chains of resistance. It may be emphasized that the obstacles to small family norms are not primarily technological but sociological. Unless the ancient prejudices, deeply ingrained beliefs and traditional cultural practices are taken into account, it will deprive us of the sources of support to any family-planning programme and blind us to the centres of resistance. A mere addition to the number of family planning clinics, which do provide the people with the necessary information and services, is likely to have limited effect, and the motivation for family-planning will not increase in view of these two aspects alone in this traditional social system, oversaturated with ancient prejudices and beliefs. Bold social-security programmes for the poor often in the grips of famine should be thought out, and the evolvement of controlled and directed intra- and interstate migration policies for employment and job opportunities should be worked out. Additionally, it may be necessary to have an intensive population-education programme, both in and out of the formal school system because of the high rate of school drop-outs. Such a programme also needs a thorough integration with the running adult-education programme. The norms of raising the marriage age and of 2 or 3 children per family should ultimately form a part of the value system.

The nomad has to settle down now, but any official attempt at inducing him to do so should invariably be tampered with sympathy and understanding of his prejudices, beliefs, social concepts and, above all, of his basic requirements. Only a humane approach can hope to win over the nomad, so that he may be interwoven with the whole fabric of the day's society in the arid zone.

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34

ASSET-LIABILITY IMBALANCES IN AGRICULTURAL SECTOR OF THE INDIAN ARID ZONE

H. S. MANN AND JAGDEESH C. KALLA

THE preparation of a dispassionate inventory of assets and liabilities of the desert lands is a prerequisite for initiating any meaningful planning. In the present context, assets and liabilities have been categorized according to their economic, social and dynamic purposes prescribed for the society inhabiting the desert region of India.

Although, irrespective of the criteria employed, the desirability of assets lies in their positive and greater value than the liabilities, the increments in liabilities do not necessarily indicate a destitution of society in the socio-dynamic sense. The incurrence of liability by society is often necessary for creating conditions conducive to an enhanced standard of living. Social liability by the same token of argument does not necessarily ensure the welfare of society.

An attempt has, therefore, been made to evaluate the economic, social and dynamic imbalance of the crucial resources to precisely identify the constraints mainly attributed to the present sluggish productive performance in the agrarian sector of the desert lands in India.

STRUCTURAL IMBALANCES IN TECHNO-ECONOMIC ASSETS AND LIABILITIES

The hot desert region in India is geographically distributed (Krishnan, 1968) in the States of Rajasthan (62 P. C.), Haryana (4 P. C.), Gujarat (20 P. C.), Andhra Pradesh (7 P. C.), Mysore (3 P. C.) and Maharashtra (0 40 P. C.). The total desert area, thus occupies 3.17 million km² accommodating 20 million human beings and 23 million cattle. The desert lands are usually subject to extremes of climatic parameters and are predominated by its non-crop uses (Table 1). This low-intensity use of land culminates in a low level of productivity and thus these lands tend to be more of a liability than of an asset. This tendency of land use is in tune with the earlier findings of Mann *et al.* (1974), in which the analysis of the time series revealed a continual shifting of the existing crop areas in the pool of degenerated land forms in eleven arid districts of western Rajasthan. The process of conversion of good agricultural land into a liability owing to its use is not peculair only to the arid districts of western Rajasthan. Almost a similar tendeney of the degeneration of land capacities, albeit to varying degrees, in the desert regions occurs in other States of India.

Another factor which pushes the present use of arid lands into the orbit of liability is the existing imbalance in the growth of human population, depending directly or indirectly for livelihood on a given piece of land. The immediate effect of the population increase on the land can be located in its faster tendencies to be fragmented into small uneconomic holdings. The results from the census of the holdings for years 1970–71 (Table 2) in respect of the States of Rajasthan, where most of the desert lands are located, reveal that the increase in population has generated a more skewed distribution of land among the rural population. About 54% of the

Table 1. Land-use pattern of the arid districts of western Rajasthan (1961, 1966 and 1971)

	Year		
	1961	1966	1971
Reporting area not available for cultivation	20,822	20,842	20,862
(a) Forest	163	150 (—7·97)	168 (+12·00)
(b) Land put to non-agric. uses	591	655 (+10·82)	662 (+1·06)
(c) Barren	2,383	2,370 (—0·54)	2,349 (—0·88)
(d) Total	3,137	3,175 (+1·21)	3,179 (+0 12)
Other uncultivated land			
(a) Permanent pasture	707	761 (+7·63)	773 (+1·57)
(b) Land for misc. tree crops	1	4 (+300 00)	2 (—50·00)
(c) Cultivable waste	4,710	4,665 (—·95)	4,561 (—2·22)
(d) Total	5,418	5,430 (+0·22)	5,336 (—1·73)
Fallow land			
(a) Fallow land other than current fallow	2,478	1,629 (—34·26)	1,911 (—17·31)
(b) Current fallow	1,580	1,475 (—6·64)	1,191 (—19 25)
(c) Total	4,058	3,104 (—23·50)	3,102 (—0 06)
Area in thousand acres			
(a) Net area sown	8,209	9,135 (+11 28)	9,247 (+1·22)
(b) Total cropped area	8,325	9,308 (+11·80)	9,577 (+2·88)
(c) Area sown more than once	116	173 (+49·13)	330 (+90·75)

Source : Compiled from Annual Digest. Issued by the Directorate of Economics and Statistics, Government of Rajasthan, Jaipur.

holdings below 5 acres have occupied only about 11% of the areas. The data also reveal a negative association between the number of the holdings and the size. Although the percentage distribution of the households (Table 3) revealed that most of the cultivator households possesed more than 10 acres, mitigating the alleged pressure of population. But when viewed in the context of the poor performance of productivity of the principal crops grown in the arid areas (Mann *et al.*, 1974), this convenience in the operational holding shrinks and tends to convert the assets-orientation of arid lands into a liability.

It can thus safely be conclued that within the present constraining framework of availability of technology and the socio-economic pressures on the pattern of land use, the productivity of land unmistakably renders lands to be more of a liability in desert regions of the country. However, this negative balance of the net worth of land can positively be converted into an asset, if for the future, a rationale land use is developed by making use of the available technology, and by considering the socio-economic pressures and the productivity constraints, and the choice of enterprises on the desert lands.

Population

The importance of combining human effort with land for its productive use is too well known to merit a mention. The past-comparative review of the data on population has revealed that the Indian population has seldom been subjected to more quantitative pressures of population than its counterpart (Malhotra *et al.*, 1972). However looking from the arid-zone standards which are characterized by less productive lands, the population seems to have reached its productive climax. The question of limited relevance, thus, is to seek and quantify the carrying capacity of the arid lands which would be able to withstand the presure of human population. This object can be realized if the occuptional distribution and the relative shifts of the population inhabiting the arid areas are studied. The census data at two points in time on the occupational distribution for the arid region in western Rajasthan, for example Table 4, revealed a decline of about 86% in the

Table 2. Distributional pattern, the number of holdings and the area operated by size class of operational holdings for the arid and whole of Rajasthan (1970–71)

Farmers in '0000, Area in '0000 ha

Attributes range	Arid zone		Rajasthan	
	Number of holdings (% of total)	Area (% of total)	Number of holdings (% of total)	Area (% of total)
Below 0·5	4·9053 (3·15)	3·9754 (0·30)	48 0957 (12 90)	12·4646 (0·61)
0·5– 1·0	6 6503 (4·27)	4 9228 (0 37)	45 9067 (12 32)	33·4312 (1·64)
1·0– 2·0	42·7882 (27·53)	20 9330 (1 60)	69 0620 (18·53)	100·4157 (4·93)
2·0– 3·0	12·3334 (7·93)	31·3054 (2 40)	45·5405 (12 02)	112 9353 (5·55)
3·0– 4·0	10·4140 (6·70)	66 5685 (5·10)	31·7003 (8·53)	110·5041 (5·43)
4·0– 5 0	8·0977 (5·21)	36·4270 (2·79)	22·7588 (6·12)	101·9083 (5·02)
5 0–10·0	29·4711 (18·96)	207 3805 (15·9)	57·5024 (15 43)	400·3299 (19 68)
10.0–20 0	24 0882 (15 50)	286·7126 (21·98)	33·1999 (8·40)	437·5854 (21·52)
20·0–30·0	8·1852 (5·26)	183 8560 (14·09)	9·6180 (2 58)	213·9105 (10·51)
30 0–40 0	3·6504 (2·34)	133·4590 (10·26)	3·9771 (1·06)	145·6740 (7·16)
40·0–50 0	1·7122 (1·10)	77 9235 (5 97)	1·8153 (0 48)	82 7961 (4 07)
50 0–above	3 0960 (1·99)	250·3538 (19·19)	3·4777 (0·93)	282·0983 (13 86)
Total	1155·3920 (100·00)	1304 2182 (100 00)	372 6544 (100·00)	2034 0549 (100·00)

Source: Compiled from *Report on Agricultural Census 1970–71 in Rajasthan (Mimeo).* Govt. of Rajasthan, pp. 100-254.

Table 3. Percentage distribution of cultivating households in India and arid districts, 1971 (in acres)

Rainfall districts	Less than 1 acre	1·0 to 2·4 acre	2 5 to 4·9 acre	5 0 to 9·9 acre	10·0 to 14·9 acre	15·0 to 29·9 acre	30·0 to 49·9 acre	50 and above
All-India	11·0	23·5	22·8	21·1	8·7	8 5	2·7	1·5
Less than 375 mm								
Jaisalmer	—	0·5	1·3	6·4	0·0	25·6	20·4	36·3
Bikaner	—	0 2	0·7	3·1	5·2	19 9	23 2	47 7
Barmer	0·2	0·7	2·0	5·8	8 4	23·3	24·0	35·6
Jodhpur	0 3	2 2	4·4	10·2	12·1	26·8	22·1	21·9
Churu	—	0 3	0·8	4·6	7·8	25·6	27·3	33·1
375 to 730 mm								
Nagaur	0 1	1·9	5·3	13·6	15·1	30·4	19 5	13·9
Jalore	0·2	4 1	7·3	16·9	16·2	27·8	16·2	11·3
Pali	2·0	13·8	16·0	21·3	14·9	18·6	7·8	4·6

Source: Government of Rajasthan (1974) *Census Report of Holdings in Rajasthan,* Department of Revenue, Jaipur, pp. 121.

Table 4. Distribution of working and non-working population for years 1961 and 1971 in the arid districts of western Rajasthan

	1961	1971	Change over 1961 (+ or —)
Workers	55,91,578 (44 91)*	30,90,970 (30 21)*	—5,00,608 (—86·06)
Cultivators	26,54,623 (73 93)	20,10,497 (65·04)	—6,44,126 (—75·73)
Agri. labourers	1,53,671 (4 27)	3,20,531 (10·36)	+1,66,860 (+208·58)
Mining industry	44,026 (1 22)	82,134 (2·65)	+38,108 (+188·55)
Household industry	2,38,896 (6·66)	1,00,852 (3·26)	—1,38,044 (—42 21)
Manufacturing	62,945 (1·75)	88,266 (2 86)	+25,321 (+140·22)
Construction	44,575 (1·24)	40,568 (1·34)	—4,007 (—91·01)
Trade and commerce	1,16,475 (3 24)	1,38,981 (4·49)	+22,506 (+119·32)
Transport	46,136 (1·28)	59,488 (1·22)	+13,349 (+128·93)
Other services	2,30,228 (6 41)	2,49,657 (8 07)	+18,429 (+108·43)
Non-workers	44,05,107 (55·09)*	71,40,709 (69·79)*	+27,35,602 (+162·10)
Total population	79,96,685	102,31,679	+22,34,994 (27·95)

* % to total population
Source : Compiled from *Census Report of Rajasthan for the Year 1961–1971.*

professions of the cultivators, household industries and construction. Thus the economic pressures for many cultivators might have become too heavy to continue their professions. A noticeable shift of rural occupation in favour of non-agricultural and commercial activities also probably reveals a disenchantment of the rural population towards the low returns from agriculture. The change in preference of occupations reveals that within a decade (1961–71), a massive shift from workers, cultivators, household industries and construction went to agricultural labour, mining industry, manufacturing, trade and commerce, transport and non-workers. With the existing technology and production performance of the crop sector, it can be seen that the traditional orientation of values, subsistence economy and the lack of commercialization (Wharton, 1965) will predictably make the labour to be more of a liability than of an asset. The saving grace however lies in the incorporation of livestock as a single enterprise, as in the certain north western parts (Anupgarh-Pugal Region) of western Rajasthan (Malhotra, 1966).

In other desert pockets of Haryana, Punjab and Gujarat, livestock is an important 'mixed-farming' enterprise. This enterprise, by virtue of its relative stability, and employment-absorption capacity tends to minimize the liability of the rural labour force.

Another dimension of the problem of labour force as a resource is its consumption capacity of what it produces. It has been established by the National Sample Surveys that almost 80% of production, coupled with fuel, light, spices, and beverages, is consumed by the labour force. This variation is more acute when cultivators, agricultural labour and non-agriculture labour in the rural sector are compared (Table 4). It can be seen from such a comparison that the major desert areas, e.g. western Rajasthan, have a more pronounced tendency to consume (exceeding 100%) of whatever is produced. Thus a further addition to the labour force at the rate of 2.7% per annum (as in the arid districts of western Rajasthan) will accentuate the continual minimization of marketable surplus. The marketable surplus is also less than proportional, because the arid societies in India, by and large, put high social premiums on conspicuous consumption and socio-religious ceremonies, leading to a further deterioration in the quality of life (Hopper, 1962; Thorner, 1962; Nakajima, 1965).

If labour as a resource has to remain as an optimum asset in the total milieu of the rural sector of the Indian arid zone, its density of dependence upon crops and livestock will have to be consciously and continually diverted to employment-absorbing agro-based industries located in the rural areas of this region itself. The labour in the agrarian sector will only be an asset if the present value of its marginal productivity is enchanced through a size-neutral and labour-intensive package of technology in the production of agricultural commodities.

Investment structure

The major transformation of the arid region from a predominantly traditional agrarian economy to one with a large, growing, modern and commercial agricultural sector has been one of the major preoccupations of the developing countries. Of the various methods, the capital-formation approach has been thought of to be one of the promising means to achieve the desired levels of economic growth. The desert region of the country has traditionally been the least attractive channel of human and capital investment. In the context of the present analysis, capital has been defined to include livestock, machinery and implements, and irrigation. Other inputs, which are directly related to the use of capital, include improved seeds, fertilizers, plant protection and water availability.

The data on the acquired capital-investment inputs for the States including the desert reveal that the acquisition of investment items, excluding livestock, is almost uniformally and negatively related to the desert area in each State. The agrarian economy of the peasant families in the desert region has more traditional and conspicuous investment (like building a house or buying a big tractor). The surveys (Sancheti, 1965; Desai, 1969-73 and Rai *et al.*, 1972-73) in the States of Rajasthan, Gujarat and Haryana revealed that the acquisition of land and land rights, livestock, consumer durables and ornaments formed the more important components of the investment by the rural families of the desert regions of the State.

(*a*) *Agriculture machinery and implements*: It is natural to expect an increase in the traditional and modern investment inputs, because any transfer of land from one to another generation inevitably will lead to division in the ownership of resources. This division will naturally lead to the repetitious creation of assets in the agricultural sector characterized by brisk shifts in the population parameters. For comparative purposes, in the arid districts of Rajasthan, the data on machinery and implements, e.g. ploughs, cane-crushers, pumps and tractors, revealed a continually increasing trend for the years under consideration (Table 5). The results confirm that despite a spurt in the acquisition of modern investment inputs, e.g. pumps, the traditional investment items did not show a consequent decline, although this increase in the modern investment might have been responsible for enhanced productivity. The increase in the number of tractors in this region is again dubiously paradoxical. An instance of the increase in the tractor power in 11 arid districts of Rajasthan resulted in an increase in the area under cultivation (Table 1) which was mostly converted from barren, cultivable wastes, and fallows. Additional production has thus been realised at the expense of exploitative area-expansive land use. The tractor power in the arid areas of western Rajasthan had also a massive substitution potentiality for bullock-power. One tractor in 1961, 1966 and 1972 had the potentials to replace 102, 78, and 150 bullocks respectively. The introduction of the tractor can, thus, be a liability because of its replacement potential of the bullock power, so naturally adapted, coupled with further additions to the import bill of diesel oil. Despite the proven low marginal-value productivity of investment inputs (Kalla and Vyas, 1972), the farmers in the arid areas continue to acquire traditional investment inputs. This pattern pushed the total capital structure towards liability. The balance in favour of assets as against the liability of machinery and implements can only be established, if the present redistribution of land allows for an equitable acquisition of modern investment items which will have scale-neutral economic properties. The provision of equitable irrigation will further enhance the productivity of the modern assets.

Table 5. Quinquennial changes in the acquisition of agricultural machinery and implements in the arid districts of western Rajasthan (1961–71)

	Year		
	1961	1966	1971
Ploughs	9,47,043	10,22,548 (+7·97)	10,91,733 (+6·76)
Carts	2,20,822	2,58,816 (+17·20)	2,42,351 (—6·36)
Sugarcane-crushers	4,008	4,541 (+13·30)	7,113 (+56·63)
Oil engines	594	1,384 (+132·99)	10,769 (+678·10)
Electric engines	92	876 (+873·91)	9,079 (+936·41)
Persian wheels	19,313	7,140 (—63·03)	20,887 (+192·53)
Tractors	2,251	2,553 (+13·41)	6,652 (+160·55)
Ghanis	3,782	3,731 (—1·35)	2,615 (—29·91)

Source: Compiled from *Quinquennial Livestock Census Reports*, Board of Revenue (Records), Ajmer, Rajasthan.

(*b*) *Livestock*: Animal husbandry is an important productive enterprise in the desert areas of India owing to its adaptation to the uncertain and erratic climatological factors. The risk and uncertainty involved in the production of dryland crops has usually imposed upon the farmer of the desert region the necessity to diversify the production decisions in favour of livestock production to cover crop failures. Pastoral activities in the arid areas occupy a vital place because of its capability to use nearly the whole of the land. Despite its vitality, the livestock sector is usually characterized by a low-key performance and a certain amount of vulnerability which leads to a continuing nomadism of the cattle-breeders.

The recent estimates of the population of livestock indicate that the Indian arid zone abounds in livestock population. The arid region of Rajasthan, in particular (Table 6), reveals that cattle, sheep, goats and camels constitutes the majority of the animals. It can be seen that during a five-year period, only goats, camels and pigs, and during the succeeding five-year period, goats, buffaloes, camels and pigs registered an increase. Whereas the bullock population from among the total cattle population remained almost constant (20%), the milch animals accounted for most of the quinquennial variations in the population. It can thus be seen that the population of the livestock themselves has a pronounced tendency to increase and leads to grazing stress. It has been estimated that for these three years under consideration, the arid districts of western Rajasthan had 32.55, 33.48 and 23.39% of fodder short of its demand in 1961, 1966 and 1972 respectively. This shortage of fodder, coupled with that of water in bad years, and in the remote hinterlands is mainly responsible for the association of nomadism (Table 7) with pastoral activities. For instance, irrespective of the severity of climatic factors, animal outmigration from the arid districts, such as Jaisalmer, Barmer, Pali, Jodhpur and Bika-

Table 6. Distribution of livestock population among arid districts of western Rajasthan (1961, 1966 and 1971)

	1961	1966	1972
Cattle	44,10,470	46,89,228 (6·32)	34,80,752 (—25·77)
Buffaloes	9,67,304	10,55,180 (9·08)	11,08,764 (5 07)
Sheep	43,54,835	55,41,042 (27·23)	51,59,784 (—6·88)
Goats	34,29,127	42,55,888 (24·10)	58,14,174 (36·61)
Horses	18,496	17,023 (—7·96)	10,058 (—49·91)
Mules	285	201 (—29·47)	175 (—12·93)
Donkeys	91,962	91,270 (—0 75)	76,878 (—15·76)
Camels	6,21,340	5,54,935 (—10·68)	6,23,926 (12·43)
Pigs	5,334	5,056 (—5·39)	9,553 (89·31)
Total	1,38,67,133	1,62,09,808 (16·89)	1,42,84,358 (—11·87)

Figures in brackets show the percentage increases over or decreases from those of the previous year. +Computed from *Livestock Census* for the year under consideration, Board of Revenue (Records), Ajmer, Rajasthan.

Table 7. Percentage of traditional livestock migration from different arid districts of Rajasthan

Districts	1968–69	1969–70	1972–73	1974–75
1. Jaisalmer	22·48	17·15	54·90	N.A.
2. Barmer	29·78	6·30	—	3·98
3. Jodhpur	3·07	9 24	4·81	7·96
4. Pali	2·22	38·80	3·40	—
5. Nagaur	4·16	5·07	26·91	38·72
6. Jalore	10·58	18 14	2·75	13·23
7. Sirohi	1 66	3·99	—	33·32
8. Bikaner	26 05	1·31	4·21	2·79
9. Ganganagar	—	—	2·81	—
10. Churu	—	—	0·21	—
11. Sikar	—	—	—	—
Total	100·00	100·00	100 00	100·00

Source : Compiled from *Famine (Annual) Reports from the Famine and Relief Cell*, Government of Rajasthan, Jaipur.

ner, constituted 80%. Most of this migration, irrespective of the year under consideration, went to Madhya Pradesh, followed by inter-district wandering in Gujarat and Haryana.

It thus seems imminent that under the present set-up the livestock can be considered an asset if the reasons associated with the total dislocation of the livestock industry in the arid areas are properly identified and mitigated.

Comparative performance of resource net worth—some productivity estimations

Increase in investment inputs, such as human labour, animals and machinery may be necessary, but hardly are these sufficient conditions for the attainment of an economically optimum level of resource productivity. The measurement of the contribution for the three years (1961, 1966 and 1971) and the returns per rupee investment in the tangible resources (human labour, livestock and implements), excluding land and land improvements for the arid region of Rajasthan (Table 8) revealed that the livestock sector had consistently been more remunerative in all the years under consideration. Another notable feature of the productive resource adjustment is that crop production has uniformly been employing more labour and less implements. Thus it has not been possible for desert crop sector to follow an intensification programme for the realization of augmented crop production. Even this gain in the crop sector should be interpreted cautiously since the historical productivity performance of major crops for the last 20 years (1951–72) have revealed high degrees of variabilities and negative annual linear growth coefficients, specially for unirrigated crops (Mann *et al.*, 1974). Under such circumstances, crops can be considered an asset with great effort and under heroic assumptions. Livestock, on the other hand, have revealed more monetary profitability per unit of input employment for the years under consideration. This has a potential of enhancement, if diverse marketed and own-consumed milk products, e.g. curd, butter, *ghee*, cheese, milk powder and animal product, e.g. meat, eggs, hides and bone-meal, are separately evaluated. Livestock in the long-run analysis have been less fluctuating in their productivity performance and their profitability can be attributed to a comparatively few factors (Jodha, 1968) of production. Animal husbandry is, thus, more of an asset for arid districts and is likely to be so in perpetuity, if the population of livestock does not impair the prospects of increased carrying-capacity resulting from the adoption of new grassland-management technology.

Technology for the improvement of asset-liability balances in arid areas

The technology evolved for the rational management of arid lands is aimed at

Table 8. Estimated net monetary returns per unit of tangible resource employment in crop and livestock enterprise in arid districts of western Rajasthan (1961, 1966 and 1971)

Year	Gross returns to fixed resources of						
	Crop sector				Livestock sector		
	Per rupee return	Input ratio			Per rupee return	Input ratio	
		Implements	Workers	Bullocks		Labour	Natural feed
1961	0·1429	1	13·03	3·86	0·2231	1·6466	1
1966	0·2193	1	19·76	4·83	0·4995	2·7134	1
1971	0·3533	1	21·44	1·99	0·6521	2·4040	1

Source : Estimated from *Quinquennial Census Reports on Livestock*, Board of Revenue (Records), Ajmer, Rajasthan.

striking a balance between the use and conservation of resource endowments in this region. This procedure mainly consists in sand-dune stabilization, creation of shelter belts and wind-breakes, energy plantation, creation of improved grass cover in public grazing-lands and dryland farming, wherever technologically feasible. It has been shown that the technology of arid-land management is, by and large, an economically viable proposition. Another advantage of it is that the packages are less complex and more labour-intensive. The high labour-capital ratios incidental to the adoption of these technologies have undoubtedly a bright future for the productive absorption of surplus labour in region where most of the farm families depend on a monoculture crop programme (Kalla, 1974). Another implied aspect of the technology is its size-neutrality. Since only a limited amount of fixed capital is required to carry out these technological programmes, the concept of size-neutrality will automatically become operative, resulting in a less than disproportionate deviation in per unit costs and benefits incidental to variations in the size of the holding. This should not, however, lead one to conclude that the available arid-land management technology is snag-free. One of the most important, and at times, the only limiting factor which precludes the uniform adoption of this technology lies in its longer gestation periods. Because the pay-back periods in silvi-pastoral land-management system may vary from 5 to 15 years, it will create the bottlenecks for the subsistence farmers to adopt the technology. Further, the initial protection of the treated lands from the biotic interference may recoil in unreasonable and anti-social pressures, resulting in social tensions and disorder in society.

SOCIAL ASSET-LIABILITY BALANCES OF THE DESERT REGION

The family. Despite the effects of recent social forces leading to a tendency to prefer an individual family, the life style in the arid areas of India continues to be predominantly a joint-family system. Whereas joint family is a boon, if its every member socio-economically contributes to the family pool, the individualistic desires have to be curbed in favour of joint interests. The system of joint living also breeds tension within the members of a family and they are compelled to act on a common social stimulus. Whereas it may be economic help to develop a sense of co-operative living, the possibility of its being equally harmful to the development of individual confidence and personality cannot be denied. Under the present circumstances, a joint family can be an asset, if it is run on the basis of equitable distribution of responsibilities, work, income and expenditure.

Life-cycle obligations. 'The life-cycle' of the population inhabiting a desert region is marked by rituals and rights (e.g. *Gangoj*), social and religious ceremonies (e.g. death, marriage and birth ceremonies), social taboos and norms manifested in certain prohibitions (e.g. no agricultural operation on the 11th day of the Hindu calendar, the pursuing of poultry, piggery and other meat enterprises by Brahmins and tobacco by Sikhs). Whereas other societies in the country also follow a similar kind of 'life-cycle' pattern its effects upon the population inhabiting the desert region are economically more profound, recoil heavily and accentuate the deterioration process of their already precariously balanced economic status. These obligations are assets also in the sense that they reinforce philosophical and cultural values, leading to a psychological stability and power to face climatological catastrophes. If the economic impact of such ceremonies is reduced to its bare minimum, so that the farm families are left with more to be invested for the enhancement of agricultural production, these rituals and rights will certainly be social assets.

Group dynamics and related liabilities. The rural population inhabiting the desert region of India is basically nondynamic on the time-dimensional scale. However, a certain element of dynamism in the social interaction of certain castes is discernible in the rural society. The society in the arid zone is characteristically divided into watertight caste compartments with strictly defined norms of life. The encroachment of one group upon the socio-legal sanctions of another often ends in group factionalism. It is because of this factionalism and a concept of false prestige which give rise to frequent group clashes resulting in time-consuming, expensive and useless litigation and thus hinder the productive processes followed by society. More often than not social trivia of allowing potable water from a particular well has resulted in group feuds which eventually are sorted out at a tremendous cost and effort in courts. On the asset side, the cast structure has traditionally been responsible for gearing up an efficient division of labour for aquiring perfection in the art and craft handed down from generation to generation. It is thus natural to expect a *jat* in western Rajasthan to be an efficient farmer and a *mahajan* to be an efficient market-man.

Most of the desert region has inherited the feudalistic political structure which created conditions conducive to economic backwardness. The same system has, however, left a rich heritage and cultural style of life, courtesy, hospitableness, and crafts.

It is a fact that the too much of sunshine and too much of wind-power are the crucial factors responsible for low levels of productivity in the agricultural sector of the desert region. This liability can be converted into a life-generating asset, if both sunshine and wind-power are put to generate energy for the use of society. The dry climate, with plenty of sunshines and wind power also, leads to belief of better health and longevity (Mann, 1973), where the incidence of complex diseases is less in the region. On the liability side, it should be noted that a dusty environment is hazardous to the eyes and the respiratory system.

For the social system to operate at the optimum level it is neccessary that the social bottlenecks are gradually removed in a conscious and planned manner. Without the achievement of social optima, the economic optima of a society will be difficult to be achieved.

CONCLUSION AND POLICY IMPLICATION

It would appear from the discussion in the preceding sections that the resources of the agrarian society in desert region of India are imbalanced and are away from the socio-economic optima. Often these attempts at correcting the resources, imbalances range from *passe romanticism* calling for a return to the traditional forms of using the desert region and thus create show pieces of natural parks for attracting more or less informed tourists, to a scientific and futuristic point of view advocating rather a disproportionate dependence on the imported technology. Resorting to the new technology should, however, not result in too abrupt a snapping off with traditional man-land relationships which exist on the basis of centuries of experience. A careful application of the package of current technology of desert land management to the remote areas endowed sparsely with infrastructural system and thus a disequilibrium in the spatial and economic parities in the pricing of inputs and outputs will go a long way in solving the development problems of this region. It is a well-known fact that the values of the marginal productivity of water, fertilizer, plant-protection material and improved seeds are comparatively lower in the desert region than in the lands located in more fortunate places and bestowed with a flexible resource-mix. It will thus be proper if the rural sector of the desert region is subjected to hold input-subsidization and incentivized product-marketing system. This object can only be achieved, if a strong case for a meticulous socio-economic planning which includes the monetary, for fiscal, physical, social and educational instruments to correct the parity imbalances of socio-economic input-output relationship, and a resource structure of desert regions is prepared. The improved technology brought to the door of the farm sector on the vehicle of such a policy instruments will go a long way in attaining the socio-economic optima subjected to the constraints of improved equality of life, so that the desert itself ceases to be a national and international liability, and the population inhabiting this region will be sealed against the despair of famines, helplessness and frequent catastrophic devastations.

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LAND-TENURE PROBLEMS AND POLICIES IN THE ARID REGION OF RAJASTHAN

N. S. JODHA

BROADLY-speaking, land tenure comprises the formal or legal provisions and conditions surrounding the ownership and utilization of land by individuals or a group thereof. In more concrete terms, the tenurial situation in a given region is reflected through a number of interrelated features, such as the pattern of land ownership and distribution, the formal and informal leasing arrangements, the various regulations relating to land owners' and users' obligations in terms of payment of land taxes and the adherence to norms and conditions determined by the State from time to time to regulate the land use (Schickele, 1950).

These essentially institutional arrangements governing a person's legal relation to the land he owns or uses take shape within the broad framework composed of physical and human factors. Physical factors, e.g. the agro-climatic complex, operating in conjunction with the state of farm technology and the human factors, e.g. the population pressure and the community's approach to the institution of private property in land and the ideal of egalitarianism, influence the land-tenure systems.

Since the right or claim on land has acted as one of the key variables in the socio-political dynamics at different stages of history, the fact of who owns how much land and under what conditions has generally been treated as an important concern of State policy (Tuma, 1965). Depending upon the importance attached to land productivity and other technical considerations, land policies also concern themselves with how lands are used. The regulation of land utilization at times is equally or more important than the regulation of land ownership, distribution, etc. This is particularly so in the case of problem areas like the arid region, where owing to the inherent poverty of the land resource, the unregulated use of land may lead to its permanent depletion and continued decline in its productivity.

The physical characteristics of the region not only condition the production potential of the land but also determine the suitability of institutional arrangements to harness the productive potential. Land tenure and related aspects in the arid zone of Rajasthan can, therefore, be meaningfully examined only in the context of physical features of the region which are of relevance to agriculture.

ARID REGION : PHYSICAL FEATURES

Some relevant details of the natural factor endowments of 11 arid districts in Rajasthan are presented in Table 1. The districts are broadly arranged in the descending order of aridity and deficiency of the land-resource base. The impact of the deficiencies of land-resource base is broadly reflected in the relative position of different districts in terms of density of population, size of farm holdings, and importance of livestock in the district.

To understand properly the implications of the physical features of the region *vis-a-vis* the land tenure and related aspects, it will be useful to start with

Table 1. Details indicating land-resource base and related aspects in the arid districts of Rajasthan

District	Mean aridity index[a]	% area irrigated[b]	% area by use capability classes of land[c]			% area given for private cultivation[d]	Av. size of optimum holding (ha)[d]	Density of population (No./km²)[e]	% of rural population	Density of cattle per		Density of sheep and goat per	
			VI & VII	VI, VII & IV	IV & III					100 ha	100 persons of rural population	100 ha	100 persons of rural population
Jaisalmer	89	0 16	100·00	—	—	13·26 (42 86)	24·60	4	84 40	2	46	13	353
Bikaner	81	0·03	100 00	—	—	38 68 (57·72)	22 08	21	58·63	9	75	12	98
Barmer	82	0·92	85·58	9 06	5·36	74 26 (67·20)	19·72	27	92·74	7	27	59	230
Jodhpur	78	1·96	69·04	15 74	15·22	77·77 (80·59)	12·83	50	68 05	21	60	60	173
Churu	78	0 02	—	76·10	23 90	88·85 (87·64)	14 73	52	70 42	25	68	54	148
Nagaur	73	1·80	—	54·83	45·17	85·54 (96 62)	8·52	71	87 72	40	65	91	139
Jalore	72	7·10	—	61·09	38·91	80 59 (93·26)	8·93	63	95·58	30	49	84	140
Jhunjhunu	72	2 91	—	52 72	47 28	80 60 (97 57)	4 52	157	82·56	55	42	102	79
Pali	71	17 22	—	22·86	77·14	65·51 (86·71)	5·14	78	88·82	53	75	101	142
Sikar	69	5·53	—	49 10	50·90	80 25 (97·10)	4 67	135	82·97	60	54	131	117
Sirohi	—	23·34	—	—	100·00	42·83 (86 51)	3·27	82	82 09	58	83	94	136
Total	—	3·22	56 33	22·52	21·15	59 01 (80 12)	9·29	44	81·30	22	88	54	223

(a) Prepared by using the Thornthwaite's method of climatic classification. For details, see Krishnan *et al.* (1969).
(b) Net irrigated area as percentage of net cultivated area. The details relate to private operational holdings. Calculated from district-wise data of *Report on Agricultural Census 1970–71 in Rajasthan*, Government Press,' Bikaner, Govt. of Rajasthan, 1975.
(c) Land classes following the FAO use-capability classification of lands for soil conservation (For details, see text). The calculations are based on the *tahsil*-level data, following the findings of *State Land Utilization Committee Report* (1960). The report, however, did not include the Sirohi District, but we have treated it as indicated above.
(d) Calculations based on the details of private land holdings (excluding State farms) culled out from the *Report on Agricultural Census* 1970–71 *op cit*. Figures in parentheses indicate the percentages of net cultivated area to the total land area assigned to ploughing.
(e) Details relating to human population are based on Census of India, 1971 and those related to animal population are based on *Livestock Census*, 1972. Cattle include a very small proportion of buffaloes also.

the use capability of lands in the region. On the basis of the *tahsil*-wise details about the soil, vegetation and water resources, a team consisting of soil scientists, agronomists and conservation experts had broadly assessed the use capabilities of the land in different districts of the arid region of Rajasthan (State Land Utilization Committee Report 1960).

The committee subdivided the whole arid region into three zones.

Zone I. All the *tahsils* or parts thereof, characterized by lands belonging to land classes VI and VII which are suitable only for pasture and range development according to the FAO use-capability classification of lands for conservation purposes.

Zone II. All *tahsils* or parts thereof, which possess mainly lands of classes VI and VII, but a few pockets of land of class IV which could be put under cultivation under a very restricted manner involving two crops intervened by long (3 to 4 years') fallowing and various conservation practices.

Zone III. All *tahsils* and parts thereof, having different proportions of lands belonging to class III (land suited to cultivation) and class IV.

The three zones account for 56, 23 and 21 per cent respectively of the total area of the arid region (Jodha and Vyas, 1969). If one ignores the small pockets of good land within the Zones I and II, nearly 79% of the land in the arid region is not suited to high land-use intensity involved in crop-farming unless transformed by irrigation.

Hence any attempt to increase their use intensity through putting them under the plough, particularly on a regular basis or by overgrazing, tends to expose them to greater erosion hazards and leads to a fall in their production potential even in terms of forage. Further, given the limitation of these lands, especially in the context of weather variability in the region, crop-farming cannot offer high and stable yields on a sustained basis as discussed by Kaul and Misra (1961), Seth and Mehta (1963), Jodha and Vyas (1969), Jodha and Purohit (1971) and Jodha (1972).

Thus, the low permissible use-intensity of the land, their low productivity and high instability of crop-farming tend to impart a comparative advantage to pasture-based livestock-farming in large parts of the arid region. In Zone II, on the other hand, restricted cultivation with conservation practices characterized by rotations between cropping and long fallows can be encouraged, whereas Zone III can support annual cropping.

IMPERATIVES FOR LAND POLICIES

For tenurial policies and land management, the situation described above has the following imperatives:

(a) Classification of the lands according to their use capabilities is necessary and the tenurial arrangements and the planning of land use can be done only after its completion.

(b) The determination and regulation of use-intensity of land in each class has to be done at the level of operating units, e.g. farm, pasture, village.

The detailed provisions through which the above imperatives can be incorporated in tenure and land-use policies have been broadly indicated in the Statement A on the following page.

The essence of the Statement A is that an individual's rights in land and his decision about the mode and intensity of land use as well as his obligations as a land owner/user have to be assessed in keeping with the requirements of different land classes. Thus the very first step towards evolving the suggested tenurial and other arrangements is the classification of lands according to their physical characteristics and their behaviour under different modes of utilization.

However, as my earlier review of land policies in Rajasthan show, the above technical basis of land classification is completely neglected in practice (Jodha, 1970). For the purpose of land-revenue administration or agricultural develop-

Statement A

The features of the three zones in the arid region of Rajasthan and the suggested provisions of tenurial and land-use policies

Features	Zone I	Zone II	Zone III
1. Land classes	VI, VII	VI, VII, IV	III, IV
2. Share in arid region(%)	56·33	22·52	21·15
3. Farm activity favoured most by the land classes	Pasture-based livestock-farming	As under Zone I, and restricted cultivation	Normal cultivation and restricted cultivation (on land class IV)
4. Objectives of tenurial policies / arrangements, as influenced by land classification	Conservation and development of land resource base for efficient livestock-farming	As under Zone I, conservation and development of land for restricted cultivation	High farm productivity with high intensity of land use on land class III and restricted cultivation on land class IV
5. Pattern of land use (Land use intensity)	Highly extensive type of land use through natural forage production on pasture/range lands	As under Zone I, and slightly intensive use through crop-fallow rotation system	Intensive cropping on land class III, crop-fallow rotation on land class IV
6. Major area of public policy	Zoning of areas for specific land uses, law relating to development, utilization, conservation of pastures/ range lands	As under Zone I, and policy for periodical land retirement from cultivation	Usual land distribution, tenancy regulation policies; land retirement policies for class IV lands
7. Ownership	Collective or individual with provision for collective action, when required	As under Zone I, with special provisions for crop lands	Individual
8. Size of holding	Extremely large (i.e., pasture holdings)	As under Zone I, and large holdings for cultivation to facilitate long fallowing.	Normal (as permitted by ceiling laws in similar dry areas)
9. Need for public regulation of land use	Very high, at district, village and pasture levels	Very high at pasture level, and high at farm level	High at farm level for land class IV
10. Issues for public regulation	Land-animal ratio, grazing rights, rotational grazing, seasonal migration, conservation measures, other issues of pasture policies	As under Zone I, and issues related to crop-fallow rotation and conservation measures on crop lands	Conservation measures and crop fallow rotation on land class IV. For land class III, similar to other dry areas
11. Basis of taxation, penalty/rewards related to land	Number of animals	Number of animals and land size, crop produce	Land-holding size, crop produce
12. Land users' obligations	Adherence to land-use regulation and conservation laws	As under Zone I	As usual, as in the case of other dry areas

ment. the lands in the arid region are not at all classified on the basis of their use capabilities. The only land classification to be found in the official land records is the 'present use' classification. This is nothing but an inventory of the uses to which the lands are being put and it has nothing to do with the use capability of the land[1].

Regarding the provision for the regulation of use-intensity too, the land policies seem to be equally indifferent to the requirements of arid lands. A few illustrations will help.

Land distribution. The tenurial situation on the eve of the formation of the Rajasthan State in 1949 was characterized by a variety of formal and informal arrangements governing the control and use of lands in different princely states. A variety of intermediaries—*Jagirdar*, *biswedar*, *muafidar*, *rajvi*, etc. existed and rack-renting, tenurial uncertainties, etc, were the common features[2]. The early land legislation of the State, therefore, tried to regulate rents, protect tenants and finally abolish the intermediaries. The actual tillers of the land were made landowners and brought into direct contact with the State[3]. Further, vast areas of submarginal lands (hitherto under grass) were distributed as private holdings for cultivation under the various legislations, in particular the Rajasthan Land Revenue (Allotment of Land for Agricultural Purposes) Rules 1957. However, while making the tenants owners of the land as well as distributing new lands to private landholders, the State did not give any consideration to the use capability of the land. Nor did it impose any obligation on the beneficiaries regarding the regulation of land utilization or collective arrangement for conservation measures, etc. In other words, in terms of imparting ownership rights, etc. the agrarian legislation in Rajasthan except the land ceiling laws, treated the desert lands or submarginal lands in arid areas on a par with the lands in well-endowed areas of the southern and south-eastern parts of the State. Its implications will be discussed later.

Land-use regulation. No land legislation deals specifically with the determination and regulation of the use intensity of land. The Rajasthan Tenancy (Government) Rules, 1955, and the Rajasthan Land Revenue Act, 1956, contain some provisions for the regulation of land use, but their approach is entirely different from what has been described above. The above legislations merely stipulate that it is the duty of the revenue officials to ensure that a given piece of land is put to the same use to which, as per the revenue records, it was put in the past. Thus through the above laws, the State attempts to regulate the use of the land as per its use status in the revenue records and not as per its physically desirable level of use intensity. In effect, this procedure tends to perpetuate the existing maladjustments in the land-use pattern.

Indeed, the Rajasthan Agricultural Lands Utilisation Act 1954 goes a step further. The traditional practice of cropping and fallowing is a compromise between the intensive and extensive type of land use in the arid area. But the above Act (Section 4) completely ignoring the traditional wisdom of the desert farmer, empowers the district collector to prohibit the fallowing of the crop lands. If the land-owner fails to cultivate the land and obstructs the alternative arrangements for cultivation made by the collector he is liable to penalty up to Rs 500 per case. Though no cases of implementation of this provision have been noted, the law itself illustrates the government's ignorance of

[1]. *Patwari* records are the ultimate source of land statistics and show that a pasture is classified as pasture not because it represents land poorer than the lands classified as crop lands, and is, therefore, suitable for grass only, but because the former *Jagirdar* or *panchayat* declared it as such in view of the nearness of the watering points or the village *abadi*, i.e. village settlement.

[2]For details, refer to the Rajasthan Protection of Tenants Act, 1949; The Rajasthan Agricultural Rent Control Act, 1954; The Rajasthan Land Reforms and Resumption of Jagir Act, 1952; The Rajasthan Land Reforms and Acquisition of Land Owners Estate Act, 1953 etc.

the nature of the problem of the arid lands.

Pasture policy. The economy of the arid region, in general, and its north-western parts, in particular, is dominated by livestock-farming. Practically, every village has some common pasture lands. But the States has no ligislation reflecting its concern for these grazing lands and no well-structured pasture policy exists. The State Government, through certain provisions of the Rajasthan Panchayat Act 1953 and the Panchayat (General) Rules 1955, has shifted the responsibility for pasture development and management to the village *panchayats.* The *panchayats*, in turn neither have technical competence nor political and administrative strength to introduce any measure to regulate stocking rates, grazing rights, rotational grazing, etc. A study revealed that not a single *panchayat* had taken up any step to manage or develop village pastures and forests. Thus, as in the past, the utilization of grazing lands is governed by informal institutional arrangement under which uncontrolled and unrestricted grazing, without any obligations to the grazing land is the rule.

Conservation measures. In the case of the arid region, the resource conservation needs to be made an essential part of the land-related policies and programmes. The only legislation regarding land conservation is the Rajasthan Soil and Water Conservation Act 1964. The second schedule of this Act enumerates a large number of conservation measures, which should form part of the schemes to be undertaken by the Rajasthan Soil and Water Conservation Board and other agencies. However, Chapter II of the Act makes it clear that the approach of the legislation is very specific and narrow. In fact, the Act provides for the framework for initiating and operating the small-scale departmental conservation schemes in any notified area. It contains no provision, whereby the farmer or a group of farmers can be compelled or pursuaded to adopt conservation measures on a 'catchment' or 'watershed' basis. Nor does it have any provision, whereby conservation measures are made an essential part of the farming system in the arid areas.

REASONS FOR NEGLECT

The absence of provision conducive to the conservation, development and efficient utilization of arid lands in the agrarian legislation of Rajasthan can be attributed to the following factors:

The land-tenure and the related policies emerged as a part of the land-reform programmes in the State during the 1950s. The primary objective of the land reforms was to replace the feudal agrarian structure by a more equitable and just agrarian system in keeping with the ideals of a democratic State. The feudal agrarian order, which had developed over a long period in the princely States of Rajasthan, had a number of exploitative features. The production, distribution and exchange relations between the land-owner and the land-user were exploitative. The land-use pattern it encouraged was not related to the land-use capabilities and hence was already over-exploitative. The land reforms were only concerned with the exploitative features of the feudal order, as they related to the tillers of land and not to the land itself. Thus the need for preventing very intensive use of land was completely overlooked, and the conservation needs of land resource base never figured in the land-reforms law. Indeed, the real consequence of agrarian reforms through the distribution of additional submarginal lands for ploughing, etc. has been to accentuate the process of over-exploitation of lands.

The neglect of the conservation needs of the arid lands in the land reforms was partly due to its relatively poor political pay-off to the government in the context of the immediate socio-political objectives of land reforms. Further, in a young State, with a long feudal background, the new policy-makers did not fully grasp the technical factors, which could impart a conservation orientation to land policies in the arid region. Moreover, it was easier to execute common land policies for the whole State rather than having specific policies for different areas. Consequently, the tenurial and other policies designed for the State as a whole have been applied to the arid region (including Zones I and II). Their implications and consequences have been discussed in the rest of the paper.

CONSEQUENCES

Land distribution. The immediate consequence of the absence of the tenurial policies which would have helped to treat the arid lands according to their use capabilities is the indiscriminate allocation or distribution of the submarginal lands for cultivation. As shown in Table 1 the extent of the area belonging to private cultivation holding alone far exceeds the extent of the lands belonging to classes III and IV (Zone III) in all the districts, except in Sirohi and Pali. Further, as the bracketed figures in the same table show, in most of the districts more than 80% of the area of private holdings is actually cultivated. This implies that the possibility of restricting the lands already distributed for less intensive cultivation (i.e., fallowing to be followed by grass, etc.) is quite limited. Even in the driest districts of Jaisalmer, Bikaner and Barmer (where lands suited to cultivation are too limited), the extent of the area of private holdings put under cultivation ranges from 43 to 67%.

Even after the distribution of submarginal lands to private land-owners, their use intensity can be kept at a low level by following a rotation comprising a crop followed by a long fallowing. But this rotation requires a fairly large size of land-holding which can permit the fallowing of a substantial area on a rotation basis. The smaller the holding, the shorter the duration of the long fallowing and, therefore, the less the chances of maintaining a low degree of land-use intensity. This fact is clealry indicated in Table 2 where the extent of the old fallows (i.e., fallows other than the current fallows), representing the extent of the resting of the land or periodically using it for forage rather than for crop production declines with the decline in the size of the holding.

An interesting inference which can be drawn from Table 2 is that in the absence of statutory measures to regulate it, the use intensity of arid lands can be indirectly influenced by a proper distribution of land holdings. In other words, farmers can be induced to keep the use intensity at a lower level through the provision of bigger land holdings, which are conducive to cropping followed by a long fallow.

The system implies that no newly allocated land holding should be of less than a specific size. Similarly, the existing holdings should not be permitted to be fragmented below a certain level, giving rise to holding smaller than the specific size. This amounts to the fixing of the 'floor' limit similar to a ceiling limit for arid lands. However, the land-distribution policies do not seem to be concerned about such provisions. This is suggested by the distribution pattern of land holdings obtaining in different arid districts (Table 3). Contrary to the general impression, nearly 45% of the land holdings in the arid region are less than 5 hectares. In several districts the extent of such holdings range from 48 to 83 per cent of the total holdings. Even in the driest districts, e.g. Jaisalmer and Barmer, the proportion of holdings lower than 5 hectares is more than 20%. On such holdings or even on the holdings below 10 hectares (which account for nearly 60% of the total holdings in the region), adherence to a rotation comprising cropping followed by a long fallow is quite difficult. Owing to low and unstable crop yields, even a farmer with 10 hectare cannot afford to keep a large portion of the area under fallow for 2 to 4 years.

Thus, under the tenurial policies, both the opening of the submarginal lands for ploughing through the distribution of such lands as private holdings and the permitting of the holding size to become smaller than required by the use capabilities of land tend to encourage the higher use intensity of land.

Table 2. Details indicating the land-use intensity by size of operational holdings in the arid districts of Rajasthan, 1970-71[a]

District	Percentage area under important land-use categories[b] on operational holding group (hectares)											
	Net cultivated area[c]				Fallow lands other than current fallow				Cultivable wasteland[d]			
	<0·5-5 0	5 0-10 0	10 0-20·0	20.0 & more	<0.5-5 0	5·0-10 0	10 0-20 0	20 0 & more	<0·5-5 0	5·0-10·0	10·0-20 0	20 0 & more
Jaisalmer	82·28	64 35	46 85	26 23	3·13	6 22	9·94	16 45	13·12	29 02	42 55	52·76
Bikaner	88·40	77·16	69 58	51 82	4·02	6·04	7·62	9·38	7·10	16·35	22 38	37·38
Barmer	89·78	81·56	74·35	63 03	8·18	14·64	18·92	22·75	1·90	3·54	6·56	13 86
Jodhpur	97·14	92 57	87·19	74 23	2·50	6 66	12·21	24 02	0·16	0·17	0·20	1·29
Churu	97·70	95·21	90 73	84·51	1·42	3 35	6·02	9 54	0·64	1·08	2·43	4·58
Nagaur	99·01	97·60	97·56	94·32	0·66	1 85	2·05	4·77	0·16	0 16	0·18	0·52
Jalore	96·97	94 96	93·23	90·30	2·76	4 61	6·30	8·18	0·13	0·21	0·23	0·85
Jhunjhunu	99·14	95·58	98·68	97 01	0 24	0 42	0·69	1·05	0·37	0·38	0·38	1·07
Pali	96·26	92 63	86 81	78·02	3 08	6·10	11·69	18·23	0 19	0 45	0·68	2·19
Sikar	98·27	97·92	97·29	94·62	0·41	0 88	1·37	2·60	0·66	0·57	0·55	1·63
Sirohi	92 65	86·72	82·33	75·30	1·65	10·73	14·49	19·27	0·97	1·15	1·64	3·14

(a) Data culled out from *Report on Agricultural Census 1970–71*, op. cit.
(b) The total of the following three categories in each holding class does not add up 100, as the area put to non-agricultural use, etc, is excluded.
(c) The net cultivated area includes the net sown area and the current fallow. For explanation see text.
(d) It includes other uncultivated land (excluding fallow), the proportion of which, however, does exceed even one per cent of the area in any of the groups of holdings in any district, except the largest group of holdings in Jaisalmer.

Table 3. Distribution of operational holdings by size in the arid districts of Rajasthan 1970-71[a]

District	Percentage distribution of holdings				Extent % of rented in the total holdings[b]	
	<0·5-5 0	5·0-10·0	10 0-20·0	20·0 & above	Holdings	Area
Jaisalmer	20·65	20·42	25·00	33·92	10·39	2·53
Bikaner	8·34	20·88	33·38	37·39	2·73	2·23
Jodhpur	37 03	21 05	21·84	20·09	6·11	2·80
Barmer	20·90	19·01	25·24	34 85	5·61	2 43
Churu	16 58	26·48	32·17	24·77	4 82	3·35
Nagaur	44·32	25 38	20·96	9·33	5·66	4·57
Jalore	48 94	23 32	18 05	9·69	4·71	3·17
Jhunjhunu	67·78	21·17	9·33	1·72	1·99	1·50
Pali	72·62	13·00	9·31	5·08	13·21	10·60
Sikar	68·61	20·14	9 40	1·86	7·23	5·17
Sirohi	82·88	11·22	4·48	1·43	22 14	15 16
Total	44·86	19·02	23·59	12·51	7·10	3·79

(a) Based on details from *Report on Agricultural Census 1970–71 in Rajasthan*, Government Press, Bikaner, Government of Rajasthan, 1975.
(b) Includes both partly and completely rented in holdings.

The degree of land-use intensity encouraged by the pattern of land distribution does not get altered by temporary land transfers through private tenancy. As indicated in Table 3 (last two columns) except in the better-irrigated districts, e.g. Pali and Sirohi, only two to ten per cent of all holdings rent any land from others. The extent of the area falling under the rented category is still smaller and ranges from 2 to 5%.

Resource depletion. The ultimate consequences of the tenurial policies and arrangement evolved during the feudal system and those initiated during the post-Independence land reforms are reflected both in terms of (i) the depletion of land resource, and (ii) the falling productivity of land.

Regarding the resource depletion, no details covering the whole of the arid region are readily available. Yet the evidence available from different locations clearly indicates such a possibility. At several locations, the following consequences of mismanagement of arid lands have been noted: the deterioration of fertile lands due to the removal of top soil or the submersion of fertile land under shifting sand-dunes (Ghose *et al.*, 1968; Anon. 1965); the conversion of fertile lands into patches of saline wastelands in the low-lying areas near the seasonal streams (CAZRI 1964-65); the drying up of dug wells or the increased salinity of well waters[3]; the replacement of superior perennials by inferior ones or annual grasses including non-edibles in the grass-lands (Prakash *et al.*, 1964); the increased population of 'malformed' or 'stunted trees'; and finally the increased human miseries reflected by an increased extent of seasonal migration and the accentuated process of pauperization through recurrent famines (Jodha, 1975).

Declining crop yields. The impact of extending crop-farming on submarginal lands, as encouraged by the tenurial policies, is revealed by Table 4. The Table presents the indices of three yearly moving average of the area and the yield of principal crops of the arid region for the period 1951–52 to 1972–73. The area under all the crops show a rising trend. Only in

[3]In the Jodhpur-Bilara region, the region traditionally famous for the plenty of sweet subsoil water, nearly 22 per cent of 169 selected wells were found to be suffering from the above problems. See Anon (1967).

Table 4. Indices of three-yearly moving averages of area and yield of principal crops[a] of the arid region: 1951–52—1972–73[b]

Years	*Bajra*		*Kharif* pulses		*Jowar*		Sesamum	
	Area	Yield	Area	Yield	Area	Yield	Area	Yield
1952-53—1954-55	115·82	101 09	142·82	109 90	104·92	149·59	117·29	116 05
1953-54—1955-56	128 52	100·54	170·31	136·63	118·25	133·33	116·76	104·94
1954-55—1956-57	137·29	97·82	190·19	145·45	115·09	102·44	135·61	96·92
1955-56—1957-58	149·43	95 65	199·14	154·46	115·80	114·63	138 75	89 51
1956-57—1958-59	157·25	96·74	190·43	158 42	116·85	108 13	158 65	79·63
1957-58—1959-60	147·83	98 37	183·93	156 44	128·43	103·25	176·45	89·51
1958-59—1960-61	159·19	92·39	175·46	151·49	111·59	108·13	183·26	75·31
1959-60—1961-62	165·46	87·50	171·29	132·45	115·45	96·75	197 40	58·64
1960-61—1962-63	173·71	77·72	171·90	141·58	118·60	77·24	206·82	60·50
1961-62—1963-64	170·29	83·69	171·29	148·52	122·46	87·80	201·06	56·16
1962-63—1964-65	168·71	85·01	193·16	159 54	117·27	75 49	206 94	46·84
1963-64—1965-66	176·49	81·06	198·87	137·72	96·90	42·72	206 22	36·43
1964-65—1966-67	181·97	91·96	211·18	126·66	88·50	50·33	227·75	42 14
1965-66—1967-68	179 81	86·07	224 49	124 41	72·95	50·50	234·51	45·43
1966-67—1968-69	174·10	78·18	223·70	100·81	62·66	41·22	217·73	35·74
1967-68—1969-70	164 11	64 82	217·08	112 24	61 53	33·07	180 04	25 96
1968-69—1970-71	168 27	100·19	207·13	139·76	66·26	95·28	164 29	9·23
1969-70—1971-72	177·01	128·89	212·44	175·98	70·69	124·79	194 61	26 18
1970-71—1972-73	191·34	124·13	216·47	144 59	69·85	128 64	191·12	39·37

a *Bajra*, *kharif* pulses, *jowar* and sesamum covered around 60, 20,5 and 6 per cent of the gross cropped area (average of five years) respectively. The rest of the area was covered by other (nearly 17) minor crops, whose individual share rarely reached even one per cent of the gross cropped area.

b Calculations are based on district-wise area and the production data of crops from the Directorate of Land Records, Board of Revenue, Government of Rajasthan (for 1951-52 to 1955-56), and *Statistical Abstracts of Rajasthan* for the rest of the period.

the case of *jowar* around 1963–64 and sesamum around 1965–66 did areas start to decline. The reasons for this decline will be mentioned shortly. The more striking feature revealed by Table 4 is that if one excludes the impact of a sequence of extremely good years (1970-71 and 1971-72) the yields in most of the crops show a declining trend. This decline is especially strong in the case of *jowar* and sesamum, a fact which partly explains the decline in their area in the later period. Once the farmers realized the futility of planting submarginal lands to crops like *jowar* and sesamum (which need relatively good soils), they shifted the area to *kharif* pulses, and to some extent to *bajra*. *Kharif* pulses, being the crops most suited to arid lands, show relatively stable, if not rising, yield trends. The rather alarming inference from Table 4 is that an increase in the area under crops has accompanied the decline in the yields of crops. Hence the efforts to raise food production through pushing submarginal lands under the plough may prove counter-productive in the long run.

THE FUTURE COURSE

The main burden of the preceding discussion is that the land policies in the past have encouraged a land-use and management pattern which is not in keeping with the requirements of the arid lands. The reversal of the process will mean the restricting of the use intensity of lands to a lower level or the adoption of complementary provisions which permit a high-use intensity without damage to the land-resource base. Restriction on the future ditribution of submarginal lands for cultivation is the first step. The retirement of lands from cultivation and back to the natural grass is quite a difficult task. In fact, in view of the increased human and animal pressure on land and the rigidity of land-use pattern encouraged in the past, the lowering down of the level of use intensity may not be possible. Hence the alternative lies in the adoption of conservation measures which enhance the permissible level of use intensity of the arid lands.

In this context, it will not be out of place to mention that progress in agricultural productivity is normally associated with the increasing use intensity of the land. At times, the whole process of agricultural growth is explained in terms of a progressive increase in the use intensity of land.[4] However, the mere intensification of land use unaccompanied by an appropriate technology may prove counter-productive, as it seems to have happened in the arid region of Rajasthan (Jodha, 1972). Thus the first step towards raising productivity or maintaining the use intensity of arid lands at a high level is to have the necessary technological complement for both crop lands and grazing lands. In the context of arid lands in the absence of irrigation facility, various conservation measures may offer the required technological complement. Conservation technology covers various measures, some of which are well-regulated farm practices, whereas the others involve the creation of physical assets. Rotational grazing and rotations between crops and a long fallow, for instance, fall in the former category. Measures, such as the stabilization of sand-dunes, the creation of shelterbelts and micro-wind breaks, the bunding of crop lands and contour-furrowing, contour-trenching, and many other soil works for range lands fall under the second category. The conservation technology, as evolved and recommended by the CAZRI, is yet to reach the farmers (Jodha, 1972). The problems of conservation technology, the solution of which is linked to the tenurial policies are discussed below:

One such problem stems from the indivisibility character of a number of conservation measures. The measures, such as sand-dune stabilization, shelterbelt creation or the bunding work or the regene-

[4]For instance, the shift from the forest fallow to the bush fallow and hence to the short fallow and then to annual cropping and lastly to multiple cropping represented successive stages towards higher degrees of use intensity, giving rise to large favourable shifts in production possibilities of the land. See Boserup (1965).

ration of range lands through a variety of earthworks, can be adopted effectively only on the basis of the catchment rather than on the basis of individual farms or parts of the catchment. These measures require collective action on the village, pasture or catchment basis (Jodha, 1967).

Similarly, some of the regulatory practices, such as the rotational use of pasutres, also require collective action. Before land reforms, when the *jagirdar* had absolute authority over the village, such collective decisions were not required. In some of the villages, the *jagirdars* used to enforce certain regulatory measures, for the utilization of pastures and village forests. Rotational grazing around different watering-points, known as *tobas*, grazing fees per animal, known as *ghasmari*, the zoning of village lands for grazing and collecting cut fodder through declaration known as *chait rakhai*, etc. are a few examples. Most of these provisions disappeared with the abolition of the *jagirdari* system. The new village *panchayats* which replaced the *jagirdars* for the purpose of village administration could not enforce such provisions (Jodha, 1967). In the changed circumstances to facilitate or enforce group decisions and action, it is essential to have some form of 'dual tenure'[5] which provides some authority for the group over the lands belonging to individual farmers in a given catchment. This system would not only facilitate the formation of land users' associations but will also help *panchayats* and revenue authorities to enforce the adoption of conservation technology.

The individual land users' obligations in terms of adherence to conservation practices should be specifically incorporated in the land laws. These laws can be enforced with liberal recourse to penalties in the case of default, and the granting of rent remission, etc. as a reward for adopting conservation measures.

The provisions involving the land users' obligations are more important in the case of grazing lands. The present practices of overstocking unrestricted and unregulated grazing, for instance, are largely in vogue, because there is no provision for grazing rights and obligations in terms of grazing fees, taxes and penalties in the case of the misuse of resources. Consequently, there is little 'private cost' for resource use. The incorporation of the above provisions in the land laws may greatly help to rationalize the utilization of grazing lands.

Finally, it may be added that land policies can play only a complementary role in ushering in the era of conservation-farming in the arid region. It cannot be a substitute for the conservation-oriented development strategy which encourages the production activities having a comparative advantage in the arid region.

[5]The term 'dual tenure', used in the absence of any more appropriate term, implies that the lands in a given catchment belong to individual farmers. But when it comes to the catchment-based treatment of the lands, all farms should be treated as belonging to the group having their land parcels in the concerned catchment. The group should have authority to undertake conservation measures. It should also be liable to punishment for the mismanagement of the catchment.

In formal arrangements, similar to the one mentioned above, already exist in predominantly Bisnoi-caste villages in the Jodhpur region where the villagers as a group, do not permit an individual farmer to cut trees, etc. in his own field. Nor do they allow the killing of wild animals—deer, rabbits, etc. in the whole of the village territory.

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GEOTHERMAL ENERGY AND ITS POSSIBLE APPLICATION IN AGRICULTURE IN THE LADAKH REGION

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THE development of regions, located at higher altitudes, where very cold conditions prevail, the reserves of fossil fuel are scanty and the periods with favourable climatic conditions conducive to agricultural growth are limited, requires the full mobilization of natural resources and the application of techniques for food production and other uses. The Ladakh District of the Jammu and Kashmir State is one of the most elevated regions of the world and is located between the great Central Himalayas and the mountains on the edge of the Tibet Plateau. Naturally, low temperatures prevail there (Table 1). Moreover, the region received scanty rain during the year (Table 2), as the Central High Himalayas act as a barrier and block the rain-bearing winds from south. Thus cold desert conditions exist in most of the Ladakh region. Generally, the river valleys are the most populated areas. However, the population density of the region is low (about 3 persons per km^2). The main occupation of the people is agriculture and trade in wool.

Energy and other supplies reach Ladakh mostly from Srinagar. Therefore, the prices of almost all things are prohibitive. Things have to be stored for the winter when the roads remain closed because of snowfall. The very high price of fossil fuel, the high rate of electricity (which at present is generated with diesel-sets) and the poor economic conditions have stood in the way of greenhouse cultivation there, despite the fact that food supplies have to be occasionally made by air. These problems can be solved to a great extent through planned and co-ordinated efforts and through a fruitful utilization of the region's solar and geothermal energy resources, which are available in plenty.

AGRICULTURAL PRODUCTS OF LADAKH

As mentioned above, Ladakh's population is very low; it is scattered and found in secluded valleys. Naturally, the crops also follow the same pattern. They are raised with irrigation along the river banks and on alluvial plateaux. The important areas for this purpose are the valleys of the Indus, the Nubra and a portion of the valley of the Shyok River. Barley is the dominant crop. Wheat, buckwheat, pulses, beardless barley, peas, rapeseed, millets, roots and lucerne are chief crops and are grown in carefully manured soils which are often transported from other parts. Fruits (mainly apricots and apples) are also grown in the valley near the Indus. In the neighbourhood of Pangong Tso Lake, which is located to the south-east of Leh at an elevation of 4,267 m, crops of beans and beardless barley are raised. Vegetables and other crops are grown in Ladakh to a limited extent, mainly during the short summer and autumn.

GEOTHERMAL RESOURCES OF LADAKH

It is well known that the temperature increases as we go deep down inside the earth. The normal temperature increase is about 3° C per 100 m. The average global conductive heat flow from the

Table 1. Temperature data for Leh

Year	Time	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
		Mean monthly dry-bulb temperature°C											
1958	08·30 IST	—11·5	—10 5	—1·1	5 8	6·2	11·0	16·3	14 1	10·8	6 4	—1·0	—4·9
	17·30 IST	—7·2	—4 3	4·1	11·2	10 7	16 1	23 5	9·9	16·8	11·5	6 3	1·0
1959	08·30 IST	—10 0	—9·2	—1·5	5·1	8 7	13·6	15·7	16 1	13·9	9·5	—2·1	—6·8
	17·30 IST	—2·0	—2·2	5·1	11·1	13 9	19·8	21·1	22·5	20 7	14 8	4·6	—0·5
		Maximum and minimum dry bulb temperature °C											
1955	Max.	—3·1	2·2	7·3	7·6	13·3	20·8	21·6	24·9	21 4	10 0	—	—
	Min.	—14·2	—11·4	—4 3	—3·1	1·4	6·4	8·3	10 2	4·8	2·1	—	—
1956	Max.	—5·6	0 1	5·4	11·9	19·8	23·0	24 3	24 5	22·9	12·8	8 7	—0·5
	Min.	—17·2	—12 4	—5·3	—0·7	4·8	9 3	10 1	9·8	7·0	0 0	—7·3	—10·3
1957	Max.	—5·7	—3·6	4·7	9·6	14·1	18 8	23 5	22·6	18 6	12·3	6 6	—2·6
	Min.	—15·3	—14·5	—6·6	—1·3	1·9	6·5	9 6	8·7	4 2	—1·9	—5 8	—12 9
1964	Max.	—5·5	—3 4	7·0	12 5	14·0	19·7	24·9	26·3	22 6	17·7	9·1	—0·2
	Min.	—18·0	—16·0	—7 1	—1·8	—0·7	3·6	7·4	8 2	4·3	—2 6	—7·7	—11·2
1965	Max.	—0·3	1·5	6·2	12·2	—	22·2	24 0	24·1	—	14·8	8·8	—
	Min.	—12·4	—11 0	6·9	—2·2	1·5	5 1	8·5	7 7	—	2·3	—6·2	—14·0
1966	Max.	—	6·0	8 1	12·3	15 6	21·6	24·8	25·4	18·9	—	—	4·8
		Normal temperature (°C) based on 30 years' data (1931–1960)											
	Max.	—1·4	0·6	6·8	13·0	17·6	21 8	24·8	24·4	20 9	14·6	8 2	1·8
	Min.	—13·3	—12·1	—6·1	—0 9	2·8	6·8	10·2	9 8	—5·4	—0·8	—6·4	—10·7
		Extreme temperatures (°C) based on data (1881–1974)											
	Highest	8·3 (1916)	12·8 (1953)	19 4 (1908)	23·9 (1941)	28·9 (1893)	33·9 (1882)	33 3 (1883)	32·2 (1946)	30·6 (1883)	25 6 (1916)	20·0 (1929)	13·8 (—)
	Lowest	—28·3 (1899)	—26 4 (1964)	—19 4 (1903)	—12 8 (1903)	—4 4 (1886)	—1·1 (1886)	0·6 (1929)	2 8 (1941)	—4 4 (1940)	—7 8 (1923)	—13·9 (1962)	—25·6 (1937)

Data by courtesy of India Mateorological Department

Table 2. Monthly total rainfall in inches for a few years at Leh

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1943	1·18	0·20	1·25	0·19	0·03	0·02	0·10	0·40	0·01	0·00	0·26	0·43
1944	—	0·17	0·13	0·02	0·07	0·11	0·11	1·43	0·38	0·90	0·10	1·37
1958	0·65	0·31	0·15	0·17	0·78	0·05	0·72	0·42	1·88	0·03	0·00	0·16
1959	0·04	0·45	0·46	0·20	0·00	0·16	0·26	1·54	0·70	0·24	0·64	0·02

earth's surface is 74.3 milliwatts/m². Over the Indian peninsular landmass, the geothermal gradients and heat flow vary from 1.0 to 7.5°C per 100 metres and from 40 to 104 milliwatts/m² respectively (Gupta and Rao, 1970). In Ladakh, the geothermal gradients in shallow (20–50m) exploratory boreholes in the Puga hot-spring area are very high. The lowest observed value is 32°C/m (Gupta *et al.*, 1973).

Ladakh has had no recent volcanic activity. In fact, this is true for the whole Himalayan mobile belt. However, along with the other parts of the Himalayas, Ladakh has experienced intensive tectonic and orogenic activity. Therefore, apart from the heat derived from the disintegration of radioactive elements, heat has been generated in the region owing to orogenic activity. As a part of the Himalayas, great uplifts have occurred during the last few million years in Ladakh, as a consequence of which rocks have been brought out from great depths. Heat is given out when these rocks cool. The movements also create favourable paths of heat transport from the depths. During the folding stages and in regions marked with a tendency of uplift, the emplacement of granitoids takes place, fusion occurs and magma can be locally generated owing to the pressure drop during arched block-warping of the highly heated zones of the crust. The emplacement of post-orogenic granites of various ages have been thought of in this way in the Central and Tethys Himalayas. Intrusive bodies which are younger (<10 million years old) could cause high geothermal gradients and heat flow and thus could be a possible heat source for a geothermal field of a moderate degree. Recent investigations in the Puga-Chumatang areas show the evidence of the occurrence of Miocene/Pliocene granites in the Ladakh range.

The combined effect of the abovementioned processes has resulted in the concentration of more heat at shallow depths in the earth's crust in the Ladakh region than in the normal continental areas. Therefore there seems to be a great possibility of the development and utilization of the geothermal energy resources of Ladakh not only for agricultural purposes but also for other uses.

THE HOT SPRINGS OF LADAKH

The surface manifestations of the earth's heat in the form of hot springs are numerous in the Ladakh region. A famous cluster of hot springs occurs at Puga and Chumatang. A number of prominent hot springs are located in the Nubra Valley. According to S. N. Dhar (Personal communication), the hot springs emerge at three locations in this valley, viz. at (a) Panamik, (b) Rondhu, and (c) Changlung, in a strike length of about 100 km. The water discharge from Changlung and Panamik hot springs is very large. The surface temperatures are also about 78° and 75°C. The temperature and discharge of the Rondhu spring are less than those of the Panamik springs. Four springs having temperatures ranging from 43° to 61°C have also been reported at Gaik in the Indus Valley towards the north of Chumatang (Dua and Singh, 1974). It is most likely that more hot-spring areas may be discovered through extensive surveys.

In the Puga Valley, a large group of hot springs (more than 100 in number, with water temperature ranging from 40° to 84°C), large patches of hot ground, mud pools, along with the seepage of hot water in the Puga Nala have been observed. The valley is situated towards the south-east of Leh at a distance of about 220 km from it and at an altitude of 4,400 m above m.s.l, water from some of the Puga springs is nearly at the boiling temperature (84°C) corresponding to the altitude of the springs. A large number of hot springs having temperatures from 65° to 86°C emerge at Chumatang from the bed of the Indus through fault zones on its right bank. The above two hot-spring zones are located on each side of the Indus Suture zone near the collided junction of the Indian and Eurasian plates (Gupta, 1974; Gupta *et al.*, 1975a; Shanker *et al.*, 1975).

During the last several years, various geo-investigations, including exploratory drillings, have been carried out in the Puga and Chumatang hot-springs areas (Gupta *et al.*, 1975b; Shanker *et al.*, 1975). The majority of the shallow exploratory boreholes at Puga have tapped a mixture of steam and hot water at temperatures ranging from 80 to 135°C as predicted during 1967 by the author. Boreholes at Chumatang have also shown thermal fluids.

The Puga Valley has been recognized as the most potential geothermal field in India. The chemical analysis of its spring and borehole waters indicates that they are dominated by relatively high F, Cl, SiO_2, B, H_2S and Li as well as by low Ca and Mg. The overall geochemical and thermal considerations indicate that some phase (or phases) of late magmatic activity has (or have) occurred in the area and contributes (or contribute) to heat and certain chemical constituents of the thermal waters.

The temperatures of the sub-surface reservoirs from which the Puga and the Chumatang hot springs draw the thermal water have been estimated from geochemical thermometry and are of the order of 200°–240°C (Gupta, 1974).

EXPERIMENTAL GREENHOUSE CULTIVATION AT CHUMATANG, LADAKH

It has already been mentioned in the beginning that the high cost of fossil fuel did not allow greenhouse cultivation in the Ladakh region. The conditions from the energy point of view have been so bad in the region that in olden days, the refinement of borax (which is available at Puga) at Leh had to be stopped, as it was not found economical, though there was a good demand for this product.

The prospects of the availabity of good quantities of thermal fluids at Chumatang and Puga encouraged such an attempt recently there and the feasibility of the studies on cultivation in winter in a greenhouse heated with geothermal energy has been done at Chumatang. A steel-framed glass and transparent plastic-sheet greenhouse was installed at Chumatang.

Thermal fluids from the nearby geothermal wells were led into it to heat the environment and the soil separately. The inside temperature was regulated through a controlled flow of hot water through inlet and outlet valves. It has been possible to maintain the optimum soil and environmental temperature for plant growth during winter when the mercury drops much below zero. Forty-one varieties of plants, including vegetables and fruits, e.g. strawberry, as well as flowers were planted. Very satisfactory and encouraging results have been obtained (Behal *et al.*, 1975).

PROSPECTIVE AREAS

The geotectonic considerations, as mentioned above, suggest that geothermal gradients higher than 30°C/km, most likely, will be observed in many parts of the Ladakh region. Therefore boreholes to about 1,200 m or more, when drilled in selected areas so as to tap waters, will serve as a good source of low-enthalpy (50°C) waters which can be fruitfully used for agricultural purposes. Besides, certain localized thermally anomalous areas are also there. A few prospective areas are listed below :

1. Various parts of the Puga Valley, where there are no thermal manifestations, and the soil is free from borax and other salts.
2. The area of the Indus basin in the vicinity of Gaik and Chumatang hot-spring zones.
3. The Nubra Valley.
4. The Leh Valley, which is about 10 km wide, is shut in on both sides by high peaks averaging about 5,000 m above the m.s.l.

It seems likely that deep boreholes, if drilled at carefully selected points after carrying out various geo-investigations, may tap low-enthalpy waters. However, if this procedure does not work, the earth's heat for agricultural purposes can be extracted through water circulation in two deep boreholes connected through hydrofracturing, as is being done in other countries.

Greenhouse cultivation is necessary in Ladakh for the production of food stuffs, etc., on an effective and rapid rate. Therefore to obtain substantial benefits and provide a year-round supply of vegetables (e.g. tomatoes, cabbage, cauliflower, french beans, cucumbers, lettuce, knol-knol, green leafy vegetables) and some tropical fruits, fish, eggs, chicken, etc., it is necessary that a planned and co-ordinated effort is made. The experimental greenhouse, aquaculture and poultry-farming may be started in the Ladakh region by utilizing the natural free-flowing thermal water from hot springs and also from flowing boreholes.

ECONOMIC SIGNIFICANCE

The advantage of geothermal waters is that no fuel is consumed to get its energy-giving heat. These waters can be tapped at many favourable locations and directly used for agricultural applications in cold climates. Cold desert conditions similar to those of Ladakh, occur in Oregon (USA). A company named 'Oregon Desert Farms' reaped enormous savings in the last few years turning to geothermal greenhouses to protect his vegetables from cold desert nights.

The utilization of geothermal energy in agriculture is very economical. Greenhouse-heating with geothermal energy has been estimated to cost \$ 0.399/m^2 in comparison with \$ 11.92 /m^2 operating cost with fuel-oil. Thus the ratio of geothermal to fuel-oil operating cost is 1 to 33.01, in which case the geothermal annual variable cost in agriculture in the world is \$ 2,473,854 (\$ 82,188,960/33.01), resulting in an annual saving of 79.72 million dollars (Peterson and El-Ramly, 1975).

The energy content of free-flowing thermal waters, relative to °C, from the Nubra Valley, Chumatang, Puga and Gaik hot springs of Ladakh is equivalent to about 8,000 kw. A manifold increase of the availability of this energy can be attempted by drilling boreholes. Even if one-third of this energy, which is going waste, is utilized, it will result in great saving. Low-salinity thermal waters, if found suitable, can also be used for irrigating the soil directly. The final waste saline water after heating the soil through the pipes can be further used to melt the snow and obtain the water-supply for irrigation. Other benefits will be savings in the cost of transportation of fuel and foodstuffs to the Ladakh region, the provision of cheap agriculture products, the optimum utilization of man-hours and ultimately the socio-economic development of the region,

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AN OPERATIONAL RESEARCH PROJECT FOR ARID-LAND MANAGEMENT

S. P. MALHOTRA

In spite of the availability of much valuable technical knowhow, there has been rather a slow diffusion of the newer scientific discoveries to the farmers' fields. To bridge the communication gap, the Institute launched an 'Operational Research Project' on an inter-disciplinary basis for arid-land management. On the basis of the proven findings of this Institute, the following aspects of the development of the arid region have been taken up in a cluster of five villages in the Jodhpur district:

1. Sand-dune stabilization
2. Pasture, grasses and forage development
3. Afforestation and shelter-belt programme
4. Demonstration of higher productivity of improved technology on *rabi* and *kharif* crops
5. Demonstration of higher productivity by improved technology of important vegetables and fruits
6. Demonstration of effective control of rodents
7. Community organization and programmes of technocracy
8. Sheep-development programme
9. Demonstration of gobar-gas plants, solar water-heaters, solar dryers and solar cookers.

APPROACH

To couple the social aspects of rural transformation effectively with the technological aspects, the operational problems in the transfer of technology are being tackled from the social, organizational and technical angles concurrently. A scientific-project consortium was organized at the Institute level to adopt an integrated approach to the use of available human, soil, water, plant, animal and solar-energy resources. Different subject-matter specialists available at the Central Arid Zone Research Institute, viz. the Agronomist, Horticulturist, Silviculturist, Animal Scientists, Physicist and Social Scientists, have been associated to make the programme scientist-oriented.

Also, the various State Government departments, local bodies and, above all, the farmers of the area are the participants in the programme, both at its conception and execution stages. To achieve such a collaboration, a district-level committee has been set up with the District Collector as its Chairman. Besides the nominees from the Central Arid-Zone Research Institute, one officer each from the State departments concerned with the Drought-Prone-Area Programme, Agriculture and Animal Husbandry, the Block Development Officer of the concerned *Panchayat Samiti* (Mandore) and a representative of the United Commercial Bank and five farmers of the project area act as members of this committee.

To gain a fuller knowledge of the anatomy of the society inhabiting the area, a detailed socio-economic survey was conducted before initiating the implementation of various elements of the programme. The small and marginal farmers as well as the lineage heads and the opinion leaders were identified. Sufficient time was then allocated for a rapport to develop between the project workers and the inhabitants of the area through personal discussions, the holdings of farmers' days, etc., to persuade the farmers to arrive at a consensus for adopting the various recommended practices. This was necessary to achieve ultimately a good multiplier effect and involve the total population of the area in the programme rather than to convert a few at a time through piecemeal demonstrations.

TRANSFERENCE OF ARID-LAND MANAGEMENT TECHNOLOGIES

Sand-dune stabilization

A medium-sized sand-dune belonging to a farmer, and located in the heart of the village, formed by the accumulation of fine sand on a rocky surface was taken up for stabilization and utilization. The movement of sand particles was posing hazards to the adjoining fertile cultivable lands of the farmers. This sand-dune had been lying fallow for a number of years and it had hardly any vegetation cover at the time it was taken up for rehabilitation. The owner of the dune area was motivated to carry out the technologies evolved by this Institute and to put the barren land into productive use by raising tree plantations and grasses, which, in turn, would meet his fuel and fodder requirements in about 5 years and also save the adjoining farm holdings from being engulfed by the moving sand particles (Plate r).

The sand-dune was fenced with barbed wire and angle-iron posts. Seedlings of *Acacia tortilis* and *Prosopis juliflora* were planted in pits of 60 × 60 × 60 cm. Between the rows of the trees, seeds of the grass, *Cenchrus* species, were sown. In all, 650 tree seedlings were planted 5 × 5 m apart. The establishment of the seedlings was excellent, with 90 per cent success. It has been estimated that the plantations on the dune will make it possible for the farmer to obtain 5 tonnes of fuel-wood from each hectare after every 10 years and 1 tonne of grass per ha every year, besides checking the movement of sand significantly. The farm-owner of the dune has now developed a profound attachment to this previously neglected area and has lately been taking a good deal of interest in its mainte-ance.

In another case, a sand-dune of about 16 ha, threatening the village holdings has been taken up under the stabilization project, with the co-operation of its owner. At the commencement of the rains, tree seedlings of *Acacia tortilis*, *Prosopis juliflora* and *Dichrostachys nutans* were planted, following the standardized techniques. In all, 2200 seedlings have been planted. All of them are flourishing. Tree-planting has been done in strips of 10 rows across the wind direction and a space of 50 m has been left between two strips for sowing the seeds of *Cenchrus* species. One hundred per cent survival of the tree seedlings planted during the year has been recorded, along with a fairly good establishment of the grass. This area also is expected to yield quite remunerative returns on a 10-year rotational felling schedule. The results so far are very encouraging (Plate s).

Grassland development

The land-use data of the region reveals over-saturation of cultivation and the use of marginal and sub-marginal lands for cultivation. Crop production on such marginal lands is not only low, but is also a soil-conservation hazard. Farmers were, therefore, motivated to use the marginal and sub-marginal lands as pastures and rangelands for animal production. The plots were sown with *Cenchrus ciliaris* and *Cenchrus setigerus* seeds, depending on the soil characteristics. These two grass species, planted at a spacing of 50 cm, have been found to perform very well, with their yields ranging from 2.5 to 3 tonnes per ha (dry matter) in normal-rainfall years, thereby ensuring sufficient fodder supplies for the livestock for the whole year. The farmers have realized the importance of growing grasses in their fields by setting aside a portion of their farms for this purpose.

Horticultural development

The programme of horticultural development carried out under this project has also received good support from the local farmers. These farmers have become well aware of the various varieties of fruits and have especially developed liking for the Gola and Seb varieties of *ber* and for the seedless variety of *anar*. About 4,000 *ber* seedlings have been planted so far in the fields of different farmers in the area of the Operational Research Project. The plantations have been done under unirrigated as well as under irrigated conditions with sweet and brackish water, and also in slopy, levelled and rocky areas. Two- to six-month-old *ber* seedlings were planted, and they are being budded with the improved *ber* varieties, viz. Gola and Seb. Spot-training is also offered to the farmers who are anxious to know the budding technique. The other fruit-tree introduced in the area mentioned above is *anar* (pomegranate) and, so far, two varieties, viz. Mandore and Saharanpur have been introduced.

To demonstrate to the farmers the method by which old orchards can be rejuvenated, spot demonstrations have been arranged from time to time to suggest proper pruning and other management operations. The Institute's contribution to these plantations has been to the extent of offering technical guidance and supply the seedlings. A good number of farmers have taken up orchard plantations on their own and the practice is finding a good acceptability and showing a multiplier effect.

Crop production

Our problem-orientated efforts in extension, since the inception of the Operational Research Project, have been to demonstrate the impact of the use of improved crops and varieties on the existing locals, that of the use of economical doses of fertilizers on the prevalent fertilizer-use practices, that of the use of efficient irrigation systems on the conventional channel-irrigation systems and many other crop management practices, e.g. the timely use of pesticides, insecticides, rodenticides and the maintenance of an optimum plant population, etc., which directly boost agricultural production. Among the major crops and varieties, hybrid *bajra*, castor (Aruna), wheat (Kalyansona), Kharchia 65 and potato (Kufri Chandramukhi) have been found to be remunerative substitutes for the existing crops and varieties.

With the recommended cultivation practices and the use of fertilizers based on soil-test values (40–80 kg of N/ha), the yield of *bajra* in such demonstrations ranged from 30 to 45 q/ha against 12 to 20 q/ha obtained from local varieties and with conventional cultivation practices. The introduction of castor variety Aruna not only increased the yield/ha (12 q/ha) and the net profit per unit area (Rs 2,200 per ha) over the local castor variety, but also the variety matured early and cleared the land for the *rabi* crops. This variety is being rapidly adopted by the farmers. Similar attainments were demonstrated with wheat (Kalyansona). Potato (Kufri Chandramukhi), a completely new introduction in the village, yielded 200 q/ha with the sprinkler irrigation system. All possible crop-saving measures have also been demonstrated from time to time. Increasing emphasis is also being laid on economizing the use of costly inputs, such as fertilizers and water. The integrated use of organic and inorganic manures, weedicides, intercrops (legumes) and the introduction of drip and sprinkler irrigation systems are some of the technologies which are being demonstrated to meet such objectives.

Our technologies and packages of practices have received wider acceptance in the area and a large number of farmers have adopted the recommended packages of practices in respect of *bajra*, castor, *moong* and *moth* during the *kharif* and wheat, *raya*, mustard and potato in the *rabi* season.

Rodent control

The socio-religious feelings of the inhabitants of the area were observed to override prudence in the matter of rodent control. Further, any piecemeal effort on a small-area basis is likely to fail, as rodents would surely overrun territories. This situation, therefore, warranted a necessity for the community to take up the work as its own programme. Emphasis was, therefore, laid on frequent individual and group discussions, advocating the necessity of their control, and a consensus was ultimately reached that the whole community inhabiting this cluster of five villages should adopt the programme.

The rodents mainly occupy the bunds and peripheral areas of the irrigated fields. In a pre-control rodent-population census, the average trap index in the rodent-infested area indicated 20.2 rodents/trap/24 hours, whereas the post-control census revealed 2.4 rodents/trap/24 hrs, indicating success in the eradication of the pest to the extent of 98 per cent. Such a drastic knock-down of the rodents was achieved by mixing two per cent zinc phosphide and one per cent oil with whole grains of *bajra*. The poison-bait was placed directly inside the burrows late in the evening. The farmers collected the dead rodents and buried them, but the fields emitted an unpleasant odour owing to the large number of deaths inside the burrows. There was not a single case of secondary poisoning.

Installation of solar appliances and gobar-gas plants

The introduction of alternative sources of energy in view of the desertification being caused by the overexploitation of the vegetal resources by the fast-increasing population was considered to be a dire necessity. The installation of biogas plants, solar heaters and solar cookers was, therefore, taken up. A high demand for the installation of biogas plants is an indication of the acceptability of the system by the community. The benefits that accrued to one of the farmers, in whose house a *gobar*-gas plant has been installed at a total cost of Rs 2,300 are in the forms of a saving of about 3 quintals of fuel-wood previously used by him monthly for cooking, etc., and about 1.75 litres of kerosene oil, as the gas is also being used for lighting purposes. Additionally, the farmer is getting good farm-yard manure and he no longer makes and burns dung-cakes.

OPERATIONAL CONSTRAINTS

The ignorance of the farmers regarding the new technologies before the launching of this programme, and the use by them of comparatively costly inputs, such as seed (hybrids), fertilizers (commercial) and pesticides, which were practically not in use before, took sufficient time for us to reach the take-off stage.

One of the most serious limiting factors, even after the adoption of the new technology, is the limited availability of finance to the farmers in the area of the Operational Research Project. No doubt, advances and loans through co-operative societies and certain banks have been made available in these villages, but the impact of these financing agencies has not been significant to the desired level as yet. The amount is either not sufficient to meet their requirements, or else it is not received in time, thus preventing the farmers from adopting the package of accepted technologies.

Certain technologies, e.g. the sand-dune stabilization, are accepted with difficulty by the farmers of the low-income group because of the heavy initial investment and delayed returns. Similarly, the drip and sprinkler systems of irrigation, whose merits are well appreciated by the farmers, are getting acceptance rather slowly because of the lean financial position of the majority of the farmers (Plate t).

The inability of the co-operative societies to supply seeds, fertilizers, pesticides, etc., at the doors of the farmers and in time, and preferably on credit, has been observed to be another important constraint in accepting the proven technologies by the farmers. If these facilities are made available, many of the farmers will make use of the technologies of which they are fully convinced.

The shortage of power supply has not only prevented the farmers from deviating from their conventional cropping systems, but has also prevented many of them from accepting certain improved technologies, e.g. the sprinkler and drip-systems of irrigation.

Extension activities

To overcome the above-mentioned operational constraints, apart from the help obtained through the district-level committee mentioned earlier, a sufficient number of farmers' days, field days, school children's days, etc. are organized from time to time. The highlights of the farmers' day are the demonstration of nursery techniques suitable for the arid zone, the use of fertilizers, important desert grasses, cafeteria of dry farming crops, fodder legumes, rodent control and other pest-control techniques, etc. Besides, stalls for exhibiting different types of improved agricultural implements, the sale of seeds of improved varieties of crops and the demonstration of pesticides are also organized.

Questions posed by the farmers regarding various problems faced by them in the course of the cultivation of crops, grasses and trees and regarding the utilization of water, regarding the problems of salinity, the application of fertilizers, rodent control and the choice of pesticides are answered by the scientists of the Institute. Small handouts in Hindi, providing information on different dryland agricultural techniques and those on forestry and sand-dune stabilization are distributed to the farmers on these occasions.

Each participating farmer is also given two seedlings each of some promising tree species, e.g. *Acacia tortilis* and pomegranate, and a small packet of *dhaman* grass seeds. The field days include similar activities. Similarly, on the school children's day, each visiting student is given two seedlings of a tree and some seeds of castor for planting in their home compounds.

Additionally, the institutions of Navyug Mandal and Mahila Mandal have been organized and a sufficient number of leaflets, describing the methodology and package of practices, have been prepared in Hindi for ensuring the involvement of the farmers as participants.