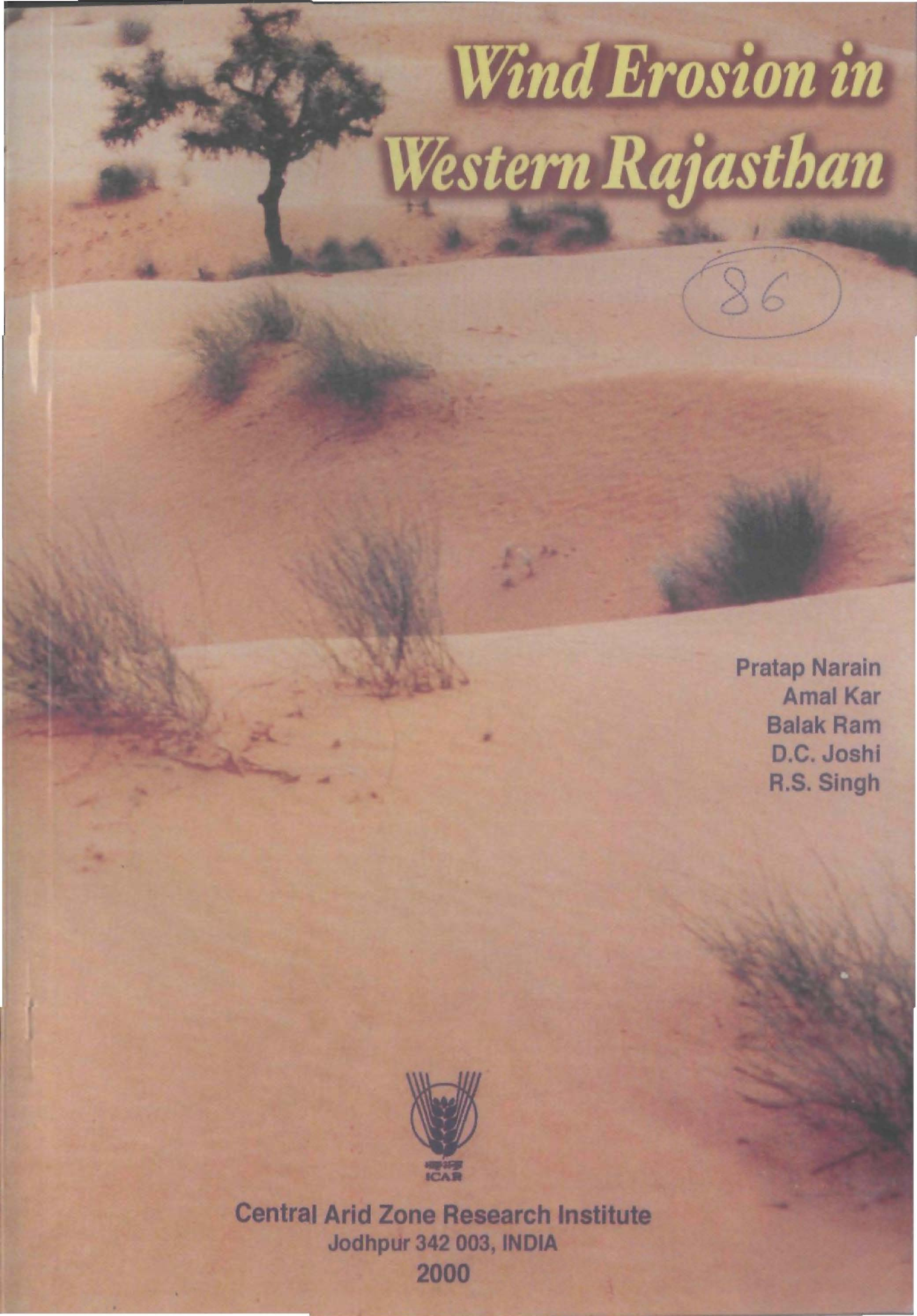

Wind Erosion in Western Rajasthan

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Foreword

Western Rajasthan is a desert, where scorching sun, hot and dry strong wind and the dominantly sandy landscape put human endurance and sustenance of life to a rigorous test. This is one of the most populated deserts in the world (both human and livestock numbers), where agriculture and livestock rearing are the major sources of livelihood. Tremendous pressure on the land in recent past has resulted in extension of cultivation to the more fragile parts sandy terrain and abused grazing of the shrinking common property resources. Consequently more lands are becoming vulnerable to wind erosion and shifting sand dunes. Each summer, large areas of the region are subjected to sand movement by wind that buries the roads and other means of surface communication, canals, settlements and tender crops in the fields. Shifting of fine sediments from crop lands leads to 'on-site' erosion of the top soil and available plant nutrients from the already impoverished land, while impairing of land quality takes place 'off-site' through covering of the fertile soil. Wind erosion is a complex phenomenon, governed by a host of factors such as wind velocity, rainfall pattern, stability of the sandy surface, vegetation cover and socio-economic pattern. A paradigm shift in desert ecology has taken place in parts of the drier western districts of the desert, especially due to the advent of canal irrigation, waterlogging and salinity. Changes in cropping pattern and micro-climate have caused alterations in the scenario of wind erosion and the socio-economics of the desert dwellers.

Although researchers at Central Arid Zone Research Institute (CAZRI), Jodhpur, and other institutions are engaged in evolving suitable technologies to control the wind erosion, what is needed for implementation of the technologies on control measures is a proper assessment of the problem, including the magnitudes of erosion, its spatial extent, enumeration of the causes in different areas and quantification of the losses. The efforts to monitor the shifts in wind erosion are welcome in refining and implementation of technologies in the region. I sincerely hope that this bulletin, along with the 1:1 million scale map on Wind Erosion that has been prepared by CAZRI, will act as a guide to understand the spatial aspects of the problem, and help in realistic planning for control measures. This will also help the planners, developers and community at large to fix the priority areas for sand control, and to decide about the interventions that will alleviate the problems. My compliments to the CAZRI team for their sincere efforts in this direction.

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New Delhi
Date: March 1, 2000.

Introduction

The western part of Rajasthan state, covering an area of 208751 square kilometres, is under arid climate. Here the land is subjected to strong wind during the hot summer months, which leads to blowing away of sand and other finer particles from parts of the landscape and deposition of the blown sediments at other localities. This process of erosion and deposition of sediments by wind is called 'wind erosion'. In the areas where this kind of erosion is predominant and continues for a long period, the process usually leads to blowing away of the top soil with its nutrients, and leaves behind a coarser substrata which is poor in nutrients. It affects the production potentials of the land. The problem becomes more serious in the agricultural fields which are ploughed before or during the high summer wind, and which remain without any protective mulch or plant cover. At the sites where deposition takes place the medium to coarse grained sand veneers the surface, and buries the productive soil. In both the cases the near-surface sediments become relatively less productive. Another major threat to agriculture from wind erosion is the injury that is caused to crops through sand blasting of the tender stems and leaves during the sand storms, and through exposure of the shallow root system by erosion of the sediments that causes eventual death of the crop plants. In the areas of deposition, the smaller crop plants get buried under sand. Wind erosion also causes serious problems to the infrastructural facilities, especially the roads, railway tracks, canals and settlements, which get buried under thick piles of sand during the sand storms. A paradigm shift in desert ecology is now noticeable in parts of western Rajasthan, especially in the drier west where introduction of canal irrigation has modified the cropping pattern, micro-climate, plant cover and socio-economic fabric of the people settled there. Although waterlogging and soil salinity are becoming manifest in many areas, the changes should also have implications for the extent and severity of wind erosion. Considering the seriousness and complexity of the problem an attempt has been made here to find out its dimensions, as well as its spatial distribution.

Western Rajasthan

Arid western Rajasthan extends from N24° 37′ 00″ to N30° 10′ 48″ and from E69° 29′ 00″ to E76° 05′ 33″. It is bounded by Punjab and Haryana states in the north, Gujarat state in the south, and the semi-arid districts of Rajasthan state in the east. In the west it has a long international boundary with Pakistan. The Aravalli hill ranges provide a natural eastern boundary with the semi-arid eastern Rajasthan. Western Rajasthan consists of the following twelve districts: Barmer, Bikaner, Churu, Ganganagar, Hanumangarh, Jaisalmer, Jalor, Jhunjhunu, Jodhpur, Nagaur, Pali and Sikar. These twelve districts account for 63.4 per cent area of the hot arid realm of India. Hanumangarh district has been carved out of

WESTERN RAJASTHAN AT A GLANCE	
Extent	N24° 37′ 00″ to N30° 10′ 48″ E69° 29′ 00″ to E76° 05′ 33″
Area	208751 km^2
Range of Mean Annual Rainfall	100-500 mm
Administrative Districts	12
Human Population (1991)	175,09,490
Rural	13,625,610
Urban	3,883,880
Human Population Density	84 per km^2
Working Population	30.27%
Cultivators	60.33% of Working Population
Agricultural Labour	9.75% of Working Population
Others	29.92% of Working Population
Total Villages	13645
Total Towns	88
Village Density	1 per 15.60 km^2
Livestock Population (1997)	28,574,530
Net Area Sown	51.13%
Net Irrigated Area	10.68%
Irrigation Intensity	133.4%
Tractors	75979
Major Crops	Kharif: Bajra, Guar, Moth, Jawar, Cotton, Sesamum Rabi: Rape & Mustard, Wheat, Gram
Forest Area	6180.45 km^2
Roads	36112 kms
Railways	3240 kms

Ganganagar district in the year 1994. Apart from these districts, about 10 per cent area each of Sirohi, Ajmer and Jaipur districts are also in the arid realm, but these are not being considered here because of the smallness of the area. Before we discuss the various facets of wind erosion in the region it is worthwhile to introduce its major bio-physical resources, e.g., climate, landforms, soils vegetation, people and their activities, all of which have bearing on the erosion processes.

Climate

There is a distinct east-west gradient of rainfall and temperature in the region. Along the eastern margin of the desert the mean annual rainfall is 500 mm, while in the westernmost part it is 100 mm. The rainfall is largely monsoon-driven. It comes between June and September. Monsoon rains account for about 95 per cent of the total received during any year. Large coefficient of variation (~40-60%) and erratic distribution during the monsoon are characteristic features of the rainfall, leading often to prolonged droughts and failure of crops (Table 1).

Table 1. Mean annual rainfall and its coefficient of variation in western Rajasthan

Meteorological station	Mean annual rainfall (mm)	Coefficient of variation of annual rainfall (%)
Barmer	267.7	58
Bikaner	293.7	55
Churu	366.3	40
Ganganagar	213.6	43
Jaisalmer	185.0	59
Jalor	369.1	53
Jhunjhunu	404.4	37
Jodhpur	361.4	53
Nagaur	315.3	50
Pali	419.5	45
Sikar	429.9	40

The mean maximum air temperature in May-June varies from 42°C in the west to 40°C in the east, but it is not uncommon to experience 48°-50°C in some years. The mean minimum air temperature is recorded during December-January (6°-10°C), when the temperature sometime dips down to below-freezing point. The winter is the period of light wind from north and north-east. From March onwards the wind peaks up and heralds in the change of season. Strong to very strong winds (often at a speed of 60-110 kmph) with sand storms are experienced during May to July when the south-west monsoon sets in. Jaisalmer in the west experience the strongest winds, with mean speed of 27.2 kmph in June, while Ganganagar in the north and Sikar in the east experience the lowest (10.7 and 11.6 kmph, respectively, in July). The mean monthly wind speeds at different stations are provided in Table 2.

Table 2. Mean monthly wind speed at meteorological stations in western Rajasthan

Station	Wind speed (kmph) in month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Barmer	7.6	7.5	9.1	10.6	12.9	14.2	12.4	10.6	9.6	7.2	5.3	6.4
Bikaner	4.6	5.1	6.5	7.3	10.1	13.3	12.8	11.0	9.4	5.3	3.5	3.7
Ganganagar	4.0	5.0	6.4	6.8	8.0	10.7	13.3	8.0	6.2	4.7	3.3	3.4
Jaisalmer	8.6	8.2	10.9	12.7	18.3	27.2	24.8	21.7	16.1	8.5	5.5	6.5
Jodhpur	8.9	8.8	9.8	10.2	15.0	18.5	16.6	12.9	10.6	6.6	5.8	7.3
Phalodi	10.0	8.8	12.9	14.1	20.7	25.6	23.6	19.4	16.6	11.6	11.8	8.3
Sikar	6.1	6.2	7.9	8.0	9.4	11.6	9.2	7.8	7.3	5.1	4.3	4.9

Source: Climatological Tables of Observatories in India (1931-1967). India Meteorological Department, 1967.

It has been observed at Jodhpur that the maximum wind speed at 2-4 m height during peak summer months is 25-40 kmph, but that it can occasionally reach as high as 60-80 kmph during the severe dust storms (Singh *et al.*, 1992).

Landforms

The present-day geomorphic processes for landscape development are dominantly aeolian (wind-driven) and fluvial (water-driven). The spatial dominance of the two processes is guided by the rainfall distribution, which decreases from east to west. Consequently, aeolian processes dominate the western part, while fluvial processes are dominant in the eastern part. The hills, rocky/gravelly pediments, colluvial plains and the older and younger alluvial plains are now dominated by fluvial processes, while the sandy undulating plains, the sand dunes and interdune plains are dominated by aeolian processes. Yet, most landforms bear the imprint of several changes in climate during the Quaternary period, between the dry and the wet phases. Most of the alluvial and colluvial plains have aeolian sand sheet deposits, both at the surface and within the Quaternary profile. The isolated saline lakes (Ranns) have been created by a complex interplay of fluvial and aeolian processes. More than 60 per cent area is under sand dunes and interdune plains. The sand dunes can be classified into the 'old' and the 'new' dunes (Fig. 1). The old dunes are mostly the parabolic, linear, transverse, star, network and major obstacle dunes. These dunes are usually 10 - 40 m high and many of them have formed

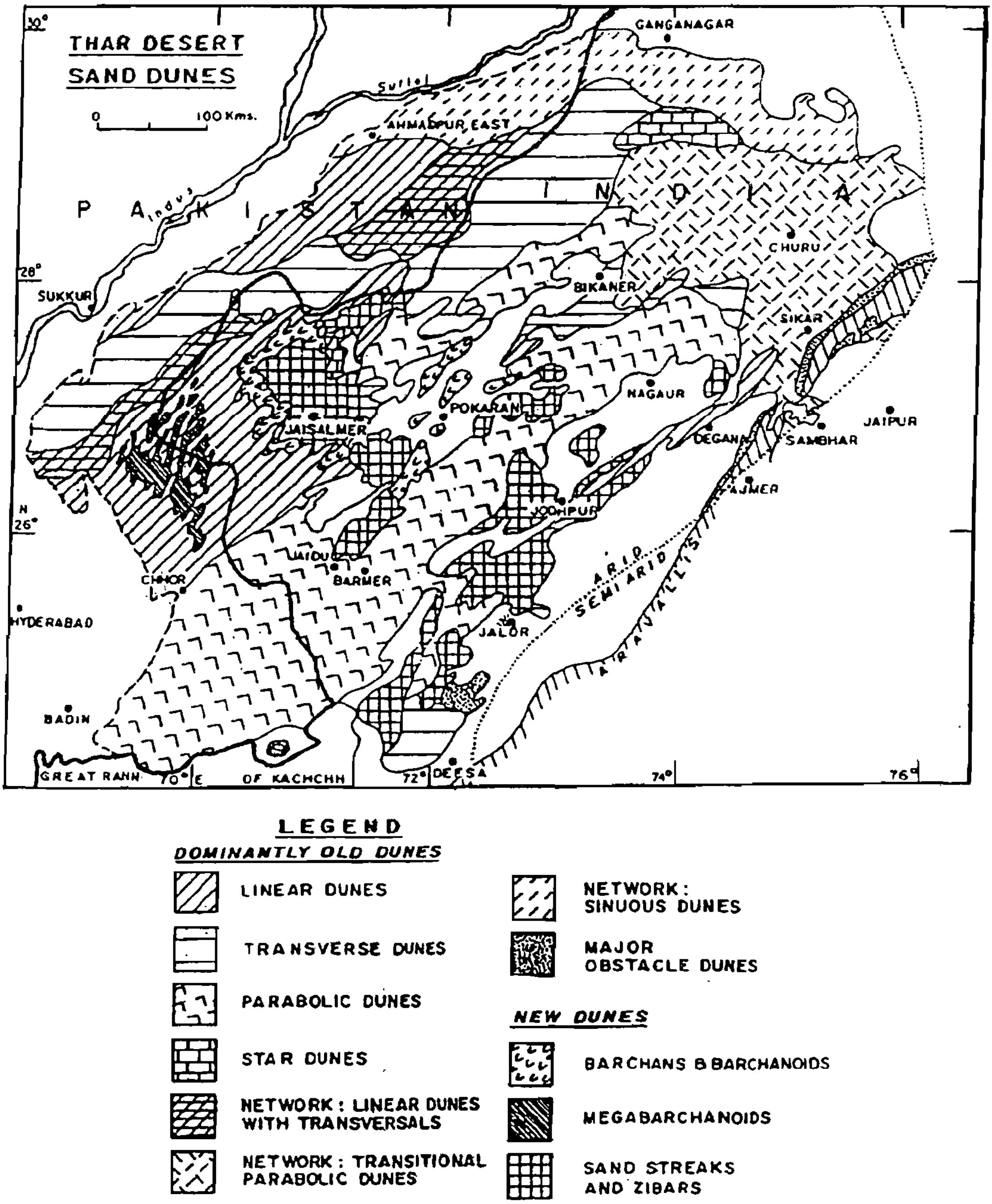

Fig. 1. Thar desert: Sand dunes.

over the last 100 thousand years. The last major period of their formation was during 11-17 thousand years before present, when the desert extended beyond its present eastern limit along the Aravalli hill ranges, to the vicinity of Alwar, Bharatpur and Delhi. The aeolian bedforms of that period in this semi-arid tract are preserved as highly dissected fossil dunes and thick sandy plains, which sometimes get reactivated due to over-use of the land, and cause localized problems of wind erosion. The new dunes include the crescent shaped barchans (2-8 m) and megabarchans (10-25 m), which are formed especially in the areas of strong wind in the west, but also where there is significant disturbance to sandy landforms due to human activities. Small sand streaks, nebkhas and stream-bordering dunes can form anywhere in the sandy plains, depending on the strength of the summer wind and stability of sandy landscape.

Soils

Soils of western Rajasthan are characterised by low contents of silt, clay and humus, but higher $CaCO_3$, gypsum and salt contents. Sand content in the soil usually varies from 60 to 90 per cent. Because of low moisture regime and hyperthermic regime weathering of minerals and pedogenic manifestations are weak. Soil profiles in arid region are characterised by the dominance of water-soluble salts, along with an impervious calcic or gypsiferous hard pan. Excess irrigation by canal water causes waterlogging and secondary salinization due to deposition of salts on the land surface as a result of evapotranspiration pull. Weak illuviation of secondary silicate minerals, segregation of lime and translocation of salts within the soil profiles have influenced the morphogenesis of soils. Using Key to Soil Taxonomy (1992) the soils of the region have been grouped under the orders Aridisols (41.0% area) and Entisols (51.8% area). The suborders, with their per cent areas, are: Torripsamments, including dunes and plains (51.7%), Cambids (30.8%), Calcids (9.3%), Gypsids (0.4%), Salids (0.5%) and Fluvents (0.1%). These have again been classified into 30 soil mapping units at family level, among which the Torripsamments (dune), Torripsamments (plain), Psammentic Haplocambids, sandy/coarse loamy Typic Haplocambids and Typic Calcigypsids are the major ones, covering 40 per cent area. The Psammentic Haplocambids occur in the central part, whereas the coarse loamy and fine loamy Haplocambids are widespread in the northern and south-eastern parts. Torripsamments associated with Gypsids are widespread in the western and northern parts. Calcids occur scatteredly in the central part.

Vegetation

There are 682 species of plants in western Rajasthan, which belong to 352 genera and 87 families of flowering plants. African elements dominate the species composition (37.0%), followed by Oriental elements (20.6%). Endemic elements are few (9.4%). Six major vegetation types have been recognised in the region. These are: mixed xeromorphic thorn forest, mixed xeromorphic woodland, mixed xeromorphic riverine thorn forest, lithophytic scrub desert, psammophytic scrub desert and halophytic scrub desert. Climate, landform, soil characteristics and water availability determine the spatial distribution of the above types. Broadly, the following four major plant groups reflect the climatic gradient from west to east: *Calligonum polygonoides - Haloxylone salicornicum - Leptadenia pyrotecnica - Acacia jacquemontii* type in the westernmost part (<150 mm rainfall), followed by *Zizyphus nummularia - Capparis decidua - Salvadora oleoides - Tecomella undulata - Prosopis cineraria* (150-250 mm rainfall), *C. polygonoides - L. pyrotechnica - Aerva persica - Crotolaria burhia - Calotropis procera - A. senegal - P. cineraria - S. oleoides* (250-400 mm rainfall), and *P. cineraria - A. nilotica - A. leucophloea - A. senegal - Anogeissus pendula - Z. nummularia* (>400 mm rainfall). Among the grasses *Lasiurus sindicus - Panicum turgidum* community is dominant in the westernmost part. This is gradually replaced eastward by *Aristida* spp. - *Eleusine compressa - L. sindicus*, followed by *Cenchrus ciliaris - C. setigerus - E. compressa*, and then by *Dichanthium annulatum - Sehima nervosum - C. ciliaris* (Meher-Homji, 1977; Saxena, 1977). Grazing tends to damage the most palatable plants first, and then the progressively less palatable species. *D. annulatum* and *C. ciliaris* are the most palatable grasses, causing them to be less frequent in occurrence.

Human population

The region is one of the most populated deserts of the world. The Marwar State of pre-independent era, which covered a large part of the present western Rajasthan, had a population of 3.41 million during 1901 census. Human population in the region has increased manifold since then, so much so that the decadal growth rate here is higher than that for the country as a whole. The post-independence growth of population is phenomenal (Fig. 2), and is largely attributable to the improvements in health care which reduced the mortality rate, high birth rates and gradual opening up of opportunities in agriculture, industries, etc. According to the 1991 census, the region has a population of 17.51 million, the average density being 84 persons per square kilometre. However, depending on the climatic and other environmental conditions, as well as resource availability, there is large spatial variation in population density (Table 3).

Jhunjhunu in the eastern fringe is the most densely populated district (267 per km^2), while Jaisalmer in the extreme west has the lowest density (9 per km^2). The population is overwhelmingly rural (77.82% of the total). Also significant to note is the fact that a staggering 69.7 per cent of the total population is categorised as non-workers, 30.1 per cent as main workers and 0.2 per cent as marginal workers. Cultivators (60.3%) and agricultural labourers (9.8%) constitute the bulk of the work force, but their spatial distribution is largely

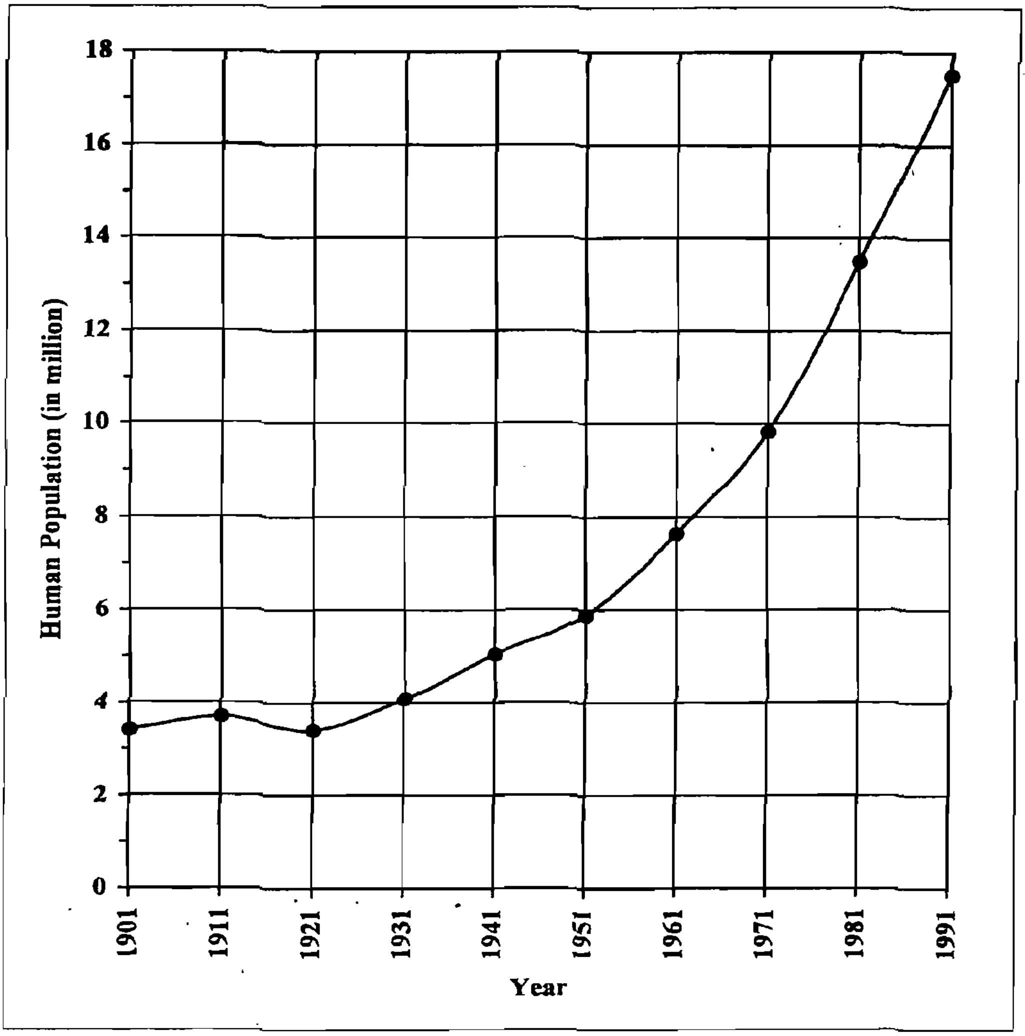

Fig. 2. Growth of human population in western Rajasthan (1901-1991).

Table 3. Human population and its density in western Rajasthan, 1991

District	Area (km^2)	Population (million)	Population density (per km^2)
Barmer	28387	1.44	51
Bikaner	27244	1.21	44
Churu	16830	1.54	92
Ganganagar	10931	1.40	128
Hanumangarh	9703	1.22	126
Jaisalmer	38401	0.35	9
Jalor	10640	1.14	107
Jhunjhunu	5928	1.58	267
Jodhpur	22850	2.15	94
Nagaur	17718	2.15	121
Pali	12387	1.49	120
Sikar	7732	1.84	238
Total	208751	17.51	84

guided by the rainfall distribution and the expanding irrigation facilities, irrespective of the fact that sandy terrain is dominant in most of the districts. This has its implications for wind erosion.

Livestock population

Livestock population has also increased significantly over the decades (Fig. 3), notwithstanding the long droughts in some decades (e.g., 1970-73; 1984-87). According to the 1997 livestock census the region has 28.57 million heads of livestock (including cattle, buffaloes, sheep, goats and camels, which together account for 99.3% of the total, as well as donkeys, pigs and horses making up the rest). Sheep and goat densities are higher in the drier districts of Barmer, Jodhpur and Jaisalmer, while buffalo density is higher in the wetter Sikar and Nagaur districts. Cattle density is more in the favourable parts of Bikaner and Jodhpur districts. Since forage consumption by the different categories of livestock is not the same, the livestock numbers were converted into Adult Cattle Units (ACUs), which provided a measure of pressure on the grazing resources (Table 4). For example, Barmer, Jodhpur and Jaisalmer districts have large heads of livestock (4.18, 3.79 and 2.48 million heads, respectively), but in terms of ACUs the districts have lower values (1.13, 1.18 and 0.58 million heads, respectively), and the ACU densities per square kilometre stand at 40, 52 and 15. In contrast, the districts of Sikar and Jhunjhunu have fewer livestock heads (1.80 and 1.25 million), consisting mostly of buffaloes, which when converted to ACUs indicated densities of 100 and 102 per square kilometre.

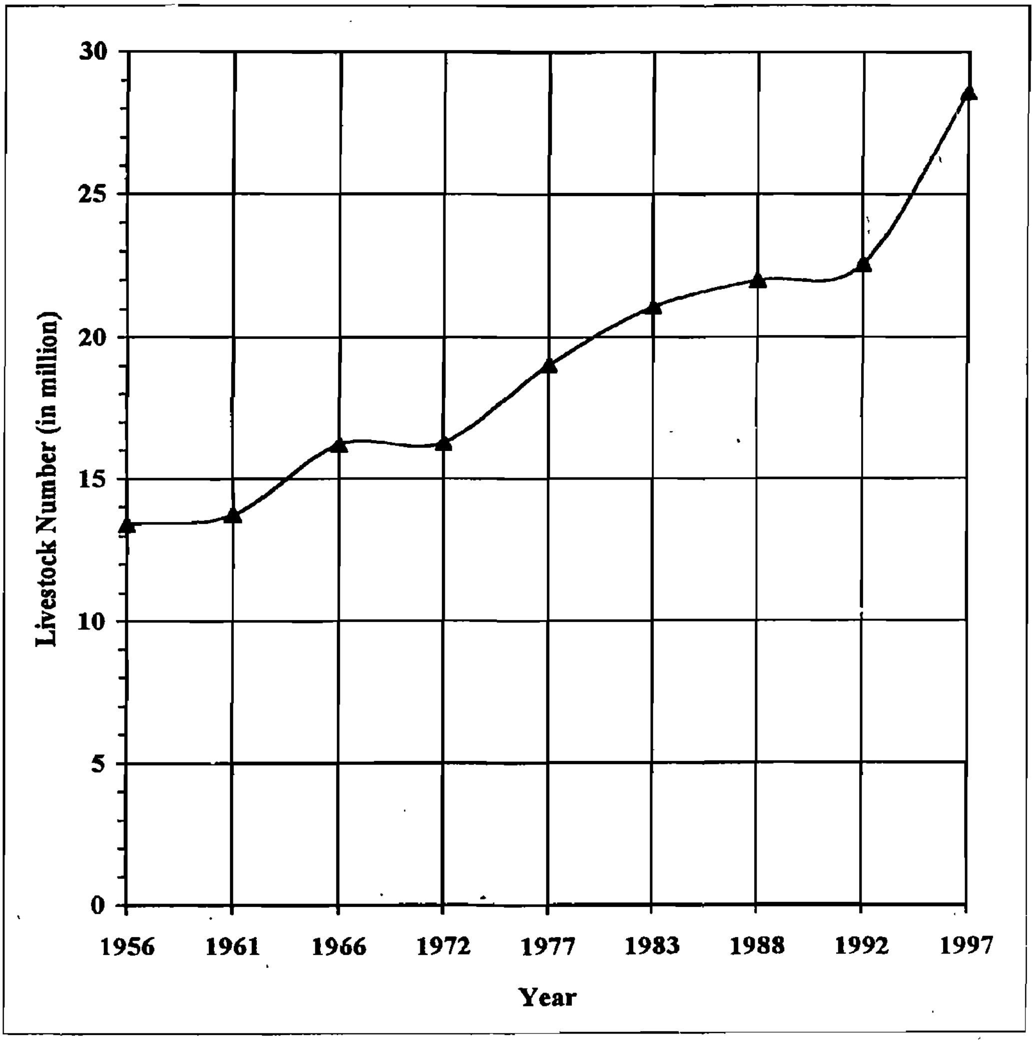

Fig. 3. Growth of livestock population in western Rajasthan (1956-1997).

Table 4. Livestock population in western Rajasthan, 1997

District	Area (km^2)	Livestock population (million)	Livestock density (per km^2)	Adult Cattle Units (ACUs) (million)	ACU density (per km^2)
Barmer	28387	4.18	147	1.13	40
Bikaner	27244	2.53	93	0.82	30
Churu	16830	2.10	125	0.72	43
Ganganagar	10931	1.43	131	0.66	60
Hanumangarh	9703	1.25	129	0.67	69
Jaisalmer	38401	2.48	65	0.58	15
Jalor	10640	1.81	170	0.70	66
Jhunjhunu	5928	1.25	211	0.60	102
Jodhpur	22850	3.79	166	1.18	52
Nagaur	17718	3.23	182	1.13	64
Pali	12387	2.74	221	0.90	73
Sikar	7732	1.80	233	0.78	100
Total	208751	28.59	137	9.87	47

Land utilization

Broadly, four major land use categories can be identified in western Rajasthan. These are: dominantly canal-irrigated croplands in the north, dominantly well-irrigated croplands in the east, dominantly rainfed croplands in the central part, and dominantly rangelands with croplands in the westernmost part. Agriculture is the dominant land use in the region. According to the 1995-96 statistics, net area sown is 51.1 per cent of the total area, but during favourable monsoon years the fallow lands and the culturable wastes are also put to mono-cropping of summer (*Kharif*) crops, so that about 85 per cent area becomes available to agriculture (Table 5).

Much of the area under fallow and culturable wastes is sandy undulating or dune-covered and, therefore, vulnerable to wind erosion, especially when put under the plough. The intensity of cultivation decreases from east to west. Availability of irrigation facilities through canal and ground water wells, has led to more area being put to double cropping. Presently 10.7 per cent area is under irrigation, and about 6.2 per cent area is now sown more than once. When compared to the situation in 1956-57, the net area sown is noticed to have increased by 39.2 per cent, while the area sown more than once has increased by a staggering 422.9 per cent. Much of this increase is due to the Indira Gandhi Canal network (especially in the western districts of Ganganagar, Bikaner and Jaisalmer), but also due to sinking of many tube wells across the desert. As a result of these developments, area under culturable waste has

Table 5. Land use in western Rajasthan, 1995-96

Category	Area (km^2)	Percentage of total reporting area
Total reporting area	208194.98	100.00
Forest	4113.42	1.98
Non-agricultural use	9008.76	4.33
Barren and uncultivable	10167.29	4.88
Permanent pasture	8324.48	4.00
Land under trees & groves	50.11	0.02
Culturable waste	40705.87	19.55
Fallow other than current fallow	14008.64	6.73
Current fallow	15369.82	7.38
Net area sown	106446.59	51.13
Area sown more than once	12813.09	6.15
Total cropped area	119259.68	57.28
Net irrigated area	22296.35	10.68
Gross irrigated area	29744.58	14.25

declined by 20.8 per cent, while the area under fallow land has declined by 32.5 per cent, suggesting that better lands from these marginally suitable units have largely contributed to the increase in net sown area. The pattern of change in land use over the decades is shown in Fig. 4.

Agro-ecological setting

Based on rainfall, landforms, soils, surface water, ground water and land use, the arid western Rajasthan has been classified into the following three agro-ecological subregions: (1) Western Sandy Plain subregion, (2) Central Alluvial Plain subregion and (3) Northern Canal Irrigated subregion. Six zones and fifteen subzones have been identified within these subregions (Table 6; Fig. 5). The classification is different from the other previous efforts towards region and subregion formation at national level in that it considers the peculiarities of the arid tract and attempts to draw the boundaries on the foundation of its major natural resource bases (Faroda *et al.*, 1999).

The spatial domains of the first two subregions largely match the two subregions mapped by National Bureau of Soil Survey and Land Use Planning, with some modifications due to terrain characteristics, while the third subregion in the northwest was necessitated by the transformations brought about by canal irrigation. Much of western sandy plains is prone to strong wind erosion, but the hard pan soil areas are less affected. The central alluvial plain, on the other hand, is dominated by medium to fine textured soils, which restrict the sand mobility.

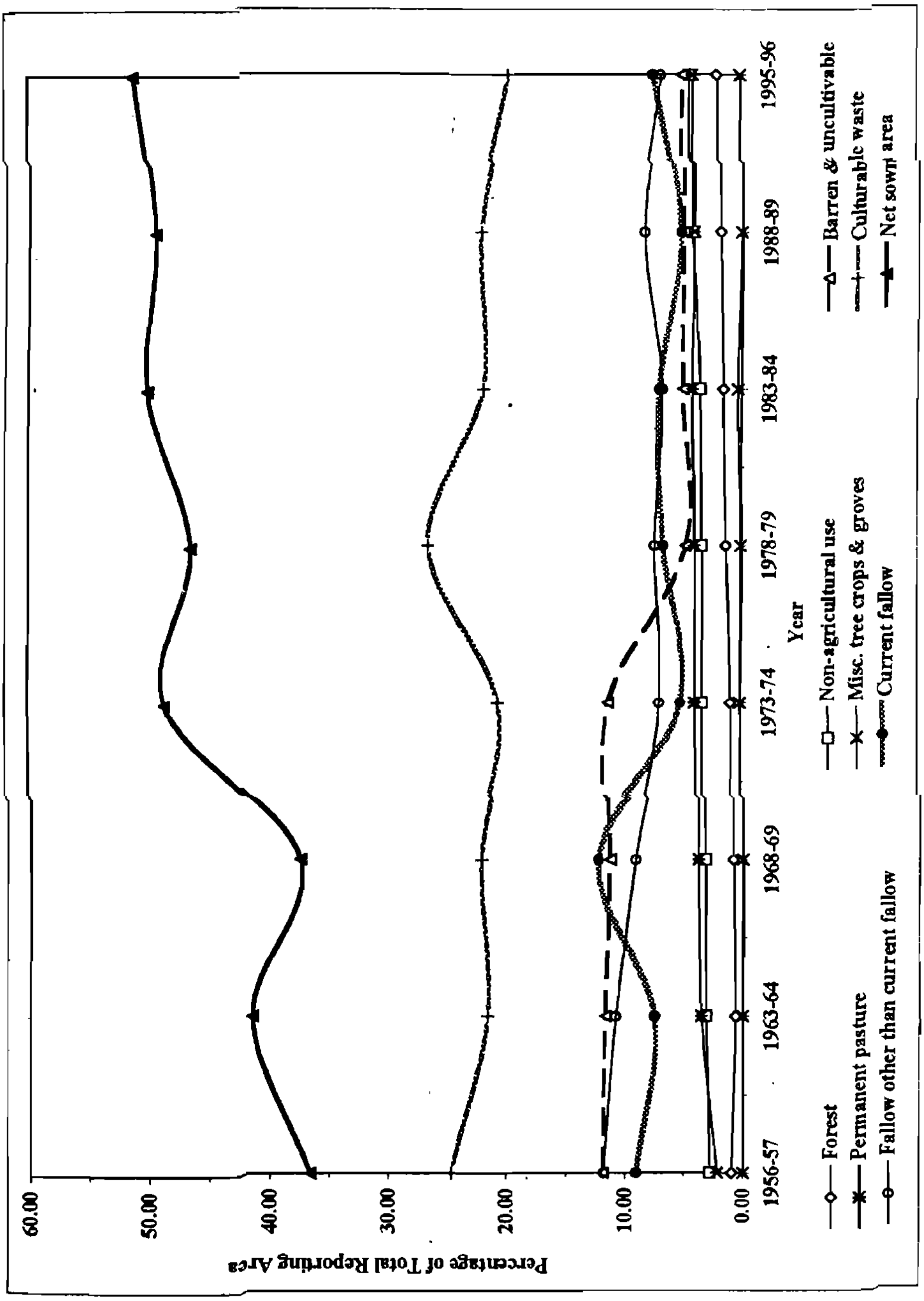

Fig. 4. Land use changes in western Rajasthan, 1956-57 to 1995-96.

Table 6. Agro-ecological zones and sub-zones in western Rajasthan

Agro-ecological zones/ sub-zones	Mean annual rainfall (mm)	Percentage of total area	Soils	Dominant land use/ major crops
Western Sandy Plain subregion				
1. Hyper-arid zone				
1.1. Hyper-arid	100	4.12	Torripsamments (dune)	Sandy waste
2. Dune complex with scrub and grasses				
2.1. Western dune complex with grassland	100-150	9.87	Torripsamments (dune)	Open grazing
2.2. Western dune complex with scrub	100-150	1.25	Torripsamments (dune)	Open grazing
3. Hard pan zone				
3.1. Hard pan soil	150-250	7.52	Petrocalcids Lithic Cambids Lithic Calcids	Limited kharif cultivation; grazing land
4. Sandy plain with scattered dunes				
4.1. Eastern dune complex with limited cultivation	250-350	6.32	Torripsamments (dune)	Kharif: bajra, moong, moth; Rabi: gram
4.2. Sandy plain with <300 mm rainfall	250-300	17.63	Torrpsamments (dune) Haplocambids Haplocalcids	Kharif: bajra, moth, guar
4.3. Sandy plain with >300 mm rainfall	300-450	2.63	Torripsamments (plain & dune)	Kharif: bajra, moong, til
4.4. Sandy plain with inland drainage	300-400	5.94	Torripsamments (plain) Haplocambids	Kharif: bajra, moong, til; Rabi: wheat, mustard

Central Alluvial Plain subregion				
5. Luni basin				
5.1. Luni basin with coarse loamy soils	300-450	12.75	Haplocambids Haplocalcids	Kharif: Bajra, guar, moong, til; Rabi: cumin, mustard, wheat, isabgol
5.2. Luni basin with fine loamy soils	300-450	6.90	Haplocambids Haplocalcids Haplosalids	Kharif: bajra, jowar, til, maize; Rabi: wheat, mustard, cotton
5.3. Mendha basin	400-450	1.34	Torripsamments (plain) Torrifluvents Haplocambids Haplosalids	Kharif: cotton Rabi: wheat, mustard, spices
5.4. Aravalli foothill	450-500	11.02	Lithic Cambids Haplocambids	Kharif: Maize, jowar, til, cowpea
Northern Canal Irrigated subregion				
6. Canal irrigated sandy plain				
6.1. Dune complex with canal irrigation	150-250	5.66	Torripsamments (dune) Petrogypsids Petrocalcids	Sand dunes: silvipasture; Interdune: ground nut, irrigated wheat, mustard,
6.2. Aeolian plain of north-east	250-300	2.01	Torripsamments (plain) Haplogypsids	Kharif: bajra, guar, cotton Rabi: wheat, mustard
6.3. Ghaggar flood plain	250-300	4.27	Torrifluvents Torripsamments (plain) Haplosalids	Cotton, wheat, rice, sugarcane

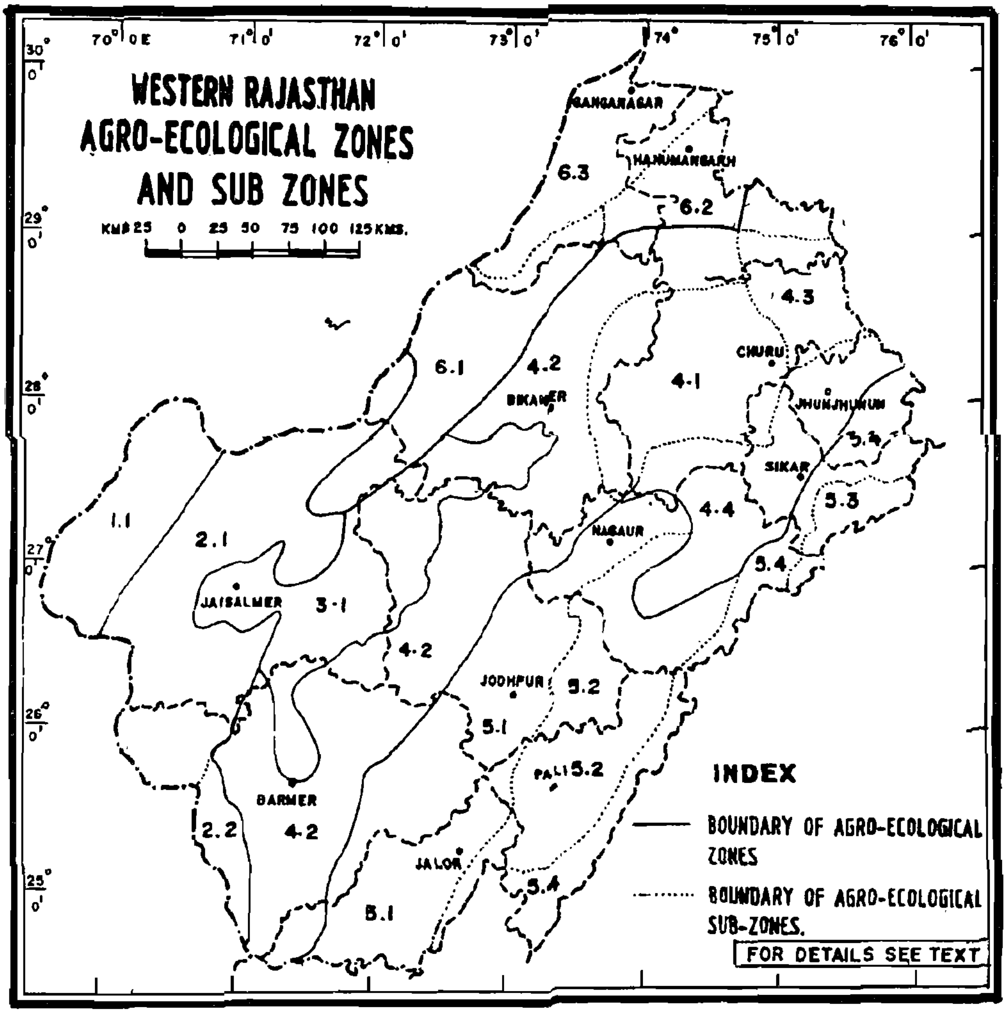

Fig. 5. Western Rajasthan : Agro-ecological zones and subzones.

Potentials of Wind Erosion

The two most important determinants of spatial variability in wind erosion are the erosivity of wind and the erodibility of terrain, which refer to the potentials of erosion. While the actual erosion at site can be measured through instrumentation and monitoring of several parameters, including wind pattern, moisture status, terrain deformation pattern, sediment volume, granulometric character, vegetation type and density, etc., such measurements are difficult to propose over large areas of a desert like ours where the variations in landscape properties and difficulties in proper instrumentation and its networking are problems to reckon with. In the absence of detailed field-based data, the qualitative assessment of potential erosion through surrogate measurement of known parameters of climate and terrain properties provides a basis for understanding the spatial dimension of the problem. These are discussed below.

Erosivity of wind

As we have noted earlier, wind erosion in western Rajasthan is restricted to the summer months when strong winds associated with the south-west monsoon sweep across the region. The sand and dust raising winds start blowing from March onward when the terrain is sufficiently dry after the previous year's monsoon rainfall (July-September), and a significant proportion of the natural vegetation, especially the annuals, are dead. Also, the crop fields become mostly barren. During May and June the wind strength increases manifold and sand storm activities increase. It continues unabated till the monsoon rains arrive, usually by the end of June at the eastern margin of the desert, along the Aravalli hill ranges, and by the middle of July in the central and western parts. As rain moistens the sandy terrain, it provides a greater resistance to the wind. Also, new plants start sprouting, which add to the resistance. The wind also falls gradually from the end of July. In other words, the period of strong sand-shifting wind can be considered as that between March and July. The north to north-east wind of the winter months is a poor agent for such activity.

Apart from this control of season on wind erosion potentials, there is also a spatial gradient in the effectiveness of the summer wind. The precipitation effectiveness, or the potential evapotranspiration (PE), decreases along the rainfall gradient from east to west, while the wind strength decreases from west to east. Therefore, the following modified Chepil formula (Chepil *et al.*, 1962; Yaalon and Ganor, 1966) was used to estimate the efficacy of wind erosion at different meteorological stations:

$$C' = 100\, v^3 / 2.9(\mathrm{PE})^2$$

where,

C′ is climatic wind erosion index;

v is the mean wind velocity at 10 m height;

PE is the Thornthwaite's measure of precipitation effectiveness; and

2.9 is the annual average climatic index at Garden City, Kansas; values at other stations are expressed as a percentage of this value.

Since summer wind alone is responsible for the erosion here, v^3 and PE were calculated for the period March to July from the long-term averages of records from the meteorological stations within the desert and its fringes. The contours drawn for the index were matched with the pattern of aeolian bedform perturbations noticed in the field and were then superimposed on the patterns of sand mobility seen on satellite imagery. It was noticed, for example, that the naturally occurring modern crescentic dunes, the barchans, start forming mostly to the west of 120 contour of the index. This conforms approximately to the 250 mm isohyet in the southern part of the desert, but not in the northern part where the wind speed is less. The aeolian processes become more efficient to the west of 480 contour. and the crescentic dunes become taller and more clustered to form elliptical fields of megabarchanoid dunes. Based on such understanding of the relationship between the bedform perturbation pattern and contour values a new scale of wind erosion index was then prepared and the categories were fixed (Kar, 1993; Table 7).

Table 7. Wind erosion categories for meteorological stations in western Rajasthan and its eastern fringe

Wind erosion index (%)	Category	Station
480 and above	Extremely high	Jaisalmer
120 - 479	Very high	Phalodi
60 - 119	High	-
30 - 59	Moderate	Bikaner, Jodhpur, Pachpadra, Barmer
15 - 29	Low	Ganganagar, Churu, Nagaur
1 - 14	Very low	Hisar, Sikar, Sambhar, Ajmer

When mapped, the south-western part of Jaisalmer district was found to be under extremely high wind erosion potential, while the area roughly between Barmer, Shergarh, Phalodi and Jaisalmer qualified as the area with very high erosion potential. The area to the east of Barmer and Shergarh, and up to Nagaur, and east of Bikaner, including Jodhpur. Pachpadra and Sanchor, was registered for moderate to high erosivity. Rest of the area in the east and north, including Jalor, Pali, Sikar, Churu, Suratgarh and Ganganagar, qualified for low to very low erosion potentials.

Erodibility of soil by wind

The inherent erodible character of the terrain and vegetation cover are important considerations for understanding the wind erosion pattern. According to Woodruff and Siddoway (1965) wind erosion is a function of several factors:

$$E = f\ (I,K,C,L,V)$$

where,

I is soil erodibility index,
K is soil ridge-roughness factor,
C is climatic wind erosion factor,
L is unsheltered median travel distance of wind across a field, and
V is equivalent vegetative cover.

The elements involved in the calculation of the above factors are numerous and somewhat complex. Moreover, it is not easy to gather the required information from many sites in the difficult desert terrain. Consequently, the method is difficult to apply for regional mapping of the phenomena.

The characteristics of the near-surface sediment composition, including soil aggregates and soil texture, are also crucial parameters to measure. A faster and somewhat reliable method for assessing erodibility of the bare soil is to refer to the proportion of dry soil aggregates of more than 0.84 mm size in it, as has been suggested by Skidmore (1988). Using this method five soil erodibility classes by wind have been identified in western Rajasthan (Kar and Joshi, 1995; Table 8).

When mapped, much of western Rajasthan came under severe and very severe categories of wind erodibility (Fig. 6), irrespective of whether the areas had similar wind erosivity or not. For example, the north-eastern part of the desert has moderate to low erosivity but the sandy character of the terrain suggests that the erodibility of the terrain is severe to very severe. Much of this area is either dune-covered or has deep sandy plains, which are regularly ploughed using traditional and mechanised implements. Therefore, even if the erosion potential is low due to insufficient wind strength, the deep ploughing of sandy soils tends to accelerate the aeolian processes in some localities, and leads to erosion of top soil in some parts and deposition of fresh sand at others.

Table 8. Soil erodibility classes by wind in western Rajasthan, using the soil aggregate method

Soil character	Average stable aggregate (%)	Erodibility class
Very deep, fine sand of dune complex	1-5	Very severe
Deep, loamy fine sand and fine sand of sandy plains and some dunes	5-10	Severe
Shallow loamy fine sand on sandy plains	5-8	Severe
Loamy medium sand of small dunes on flood plains	7-10	Moderate
Deep brown sandy loam and loamy fine sand on flat alluvial plains	10-15	Moderate
Deep flood plain soils, fine sand, sandy loam and loam	30-40	Slight
Seirozem soils with sandy loam, loam, clay loam and silty clay loam	20-50	Slight
Medium to fine textured gray brown soil	40-50	Negligible

Field Measurement of Wind Erosion

Some studies have been carried out by the Central Arid Zone Research Institute (CAZRI) to find out sediment loss due to wind erosion, as well as to understand the processes of erosion. Measurements over sand dunes during severe gusty winds at Shergarh revealed that sand grains up to 0.2 mm size were eroded at the rate of 46 kg/m^2/hour (Ramakrishna *et al.*, 1990). At Selvi near Pokaran, the rate of movement of an isolated barchan of 2.25 m height was found to be 1.70 m in 3 days of sand storm when the average wind speed was 29 kmph (Kar, 1994). The rate was, therefore, about 0.57 m per day. Data on hourly wind speed is difficult to obtain for many meteorological stations in western Rajasthan. Therefore, it is not always possible to relate measured sand transportation rates to wind velocities during the sand storm, unless the researchers are able to set up their mobile stations at right time and at the right place. Data on daily wind velocity is, however, available for most meteorological stations. Considering the difficulties in getting hourly wind data, Ramakrishna *et al.* (1990) developed a curvilinear relationship between the mean daily wind speed and the measured rates of sand erosion from a bare barchan surface at Shergarh. According to it, the minimum daily wind speed that initiated sand movement was 4 kmph. Beyond 9 kmph the sand movement increased rapidly, and over 14 kmph the mobility rate was very high. The measured wind speed and sand transport rates over a barchan at Selvi indicated the control of fetch, slope and wind direction on sand transport at different sites on the dune (Ramakrishna *et al.*, 1994; Table 9).

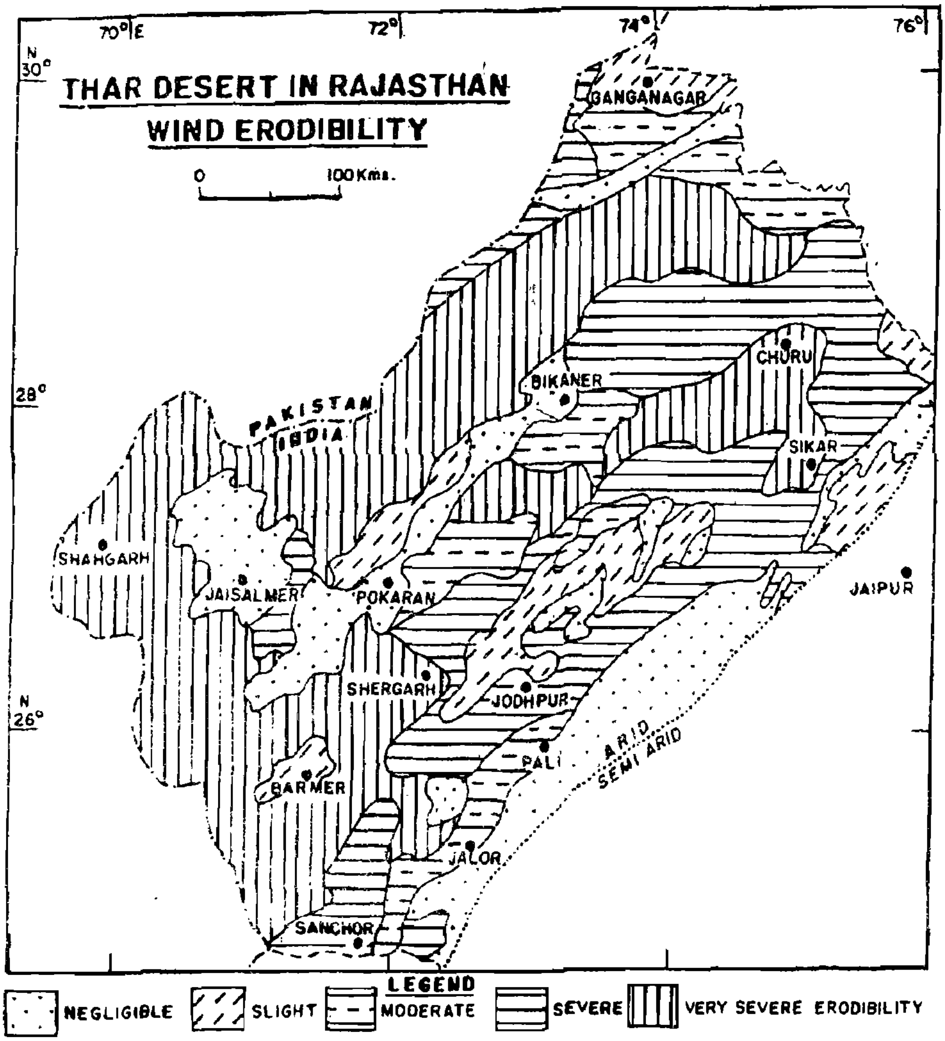

Fig. 6. Thar desert in Rajasthan: Wind erodibility.

In the sandy plains the transport rate of bare sand is governed by factors like the threshold wind velocity and sand size. According to Bagnold (1941) the threshold wind velocity to mobilise sand is roughly 4 m per second (or 14.4 kmph). Although researchers have suggested other comparable threshold values, the one suggested by Bagnold is in common use. Using this value and the mean diameter of the top sandy layer in Pokaran-Jaisalmer area (0.22 mm; 2.18 phi), the average transport rate of bare sand in the area was calculated as 35.16 tonnes per m width (Kar, 1994).

Table 9. Wind speed (m/s) and sand transport rate (kg/m^2/day) on a barchan at Selvi

Site	February		May		June		September	
	W	T	W	T	W	T	W	T
a	1.7	0.0	2.2	2.2	2.8	27.5	3.3	2.1
b	1.9	0.2	2.5	5.5	3.3	52.3	3.8	6.0
c	2.0	0.3	2.7	115.4	3.8	511.9	3.5	10.4
d	1.2	0.3	2.2	1.2	2.6	23.4	2.2	0.5
e	1.3	0.2	2.2	2.0	3.0	20.4	1.9	4.0
f	1.4	0.0	2.0	0.2	2.6	0.4	2.6	0.0

a: windward slope; b: mid-slope; c: crest; d: right flank; e: left flank; f: leeward side;
W: wind speed; T: sand transport rate.

It has been found that the loss from a sandy soil is much higher than that from a loamy sand soil, and that clod formation and vegetation are also important considerations. During a sand storm with a mean wind speed of 20 kmph, the erosion from a bare sandy soil at Bikaner was 273.7 kg/ha/day, while at Jodhpur a loamy sand soil with clod formation lost only 15.6 kg/ha/day under similar wind condition. During the same wind regime the grass cover on a sandy soil at Chandan near Jaisalmer reduced the erosion to 76.7 kg/ha/day (Gupta, 1993; Table 10). Particles smaller than 0.05 mm size were found to be least erodible.

Table 10. Soil loss under different wind speeds and terrain conditions in western Rajasthan

Mean wind speed (kmph)	Soil loss (kg/ha/day)		
	Bikaner (sandy)	Jodhpur (loamy sand)	Chandan (sandy)
5	0.5	0.3	1.0
10	120.8	1.4	8.0
20	273.7	15.6	76.7
40	1605.2	no data	1276.0

Excessive tillage before the *kharif* sowing has also been found to lower the percentage of clods greater than 5 mm size, and thus significantly increase the wind erosion. Reduced tillage, on the other hand, maintains a good clod-size distribution, and reduces wind erosion (Gupta and Gupta, 1981; Table 11).

It has also been noticed that crop stubble can significantly reduce the erosion. During a prolonged sandstorm at Bikaner the loss from a bare sandy soil was 1449 t/ha, whereas a nearby crop field with a cover of 45 cm high pearl millet stubble lost only 22 t/ha (Gupta, 1993). Long stubble of small grain crops have usually been found to be more effective than an equal quantity of short stubble. Land use practices have also been found to significantly influence wind erosion. In the sandy plains, fields deep ploughed using tractors lost soil heavily during the 22-day long sandstorm of June, 1985, while the soils under 8-12 per cent cover of natural vegetation were protected (Dhir *et al.*, 1992; Table 12). During the same sandstorm event deflation from a field cleared of vegetation cover at Chandan was 15-18 cm, and the soil lost was to the tune of 3100-3700 t/ha (Kar, 1994).

Table 11. Effects of tillage on wind erosion at Jodhpur

Soil treatment	Average condition of clods >5 mm		Wind speed (km/h)		Soil eroded	
	Clod %	Clod length (cm)	Clod width (cm)	Max.	Min.	(t/ha)
Ploughed	42.4	7.9	6.5	29.1	26.0	0.50
Ploughed and planked	12.7	2.1	1.2	29.1	26.0	40.1

Table 12. Control of land use on wind erosion during a sand storm in western Rajasthan

Land use/management	Number of sites	Mean soil loss (t/ha)	
		Range	Mean
Cultivated			
Long fallow	12	124-320	207
Untilled since previous crop	16	220-377	283
Tilled	11	756-1180	932
Disc ploughed	3	2630-3160	2837
Pasture land			
Undegraded	6	Nil	Nil
Degraded	9	217-683	472

Nutrient losses have also been reported from the sites degraded by wind erosion. For example, in the sandy terrain of Jodhpur district nutrients were measured in the cultivated lands, the culturable wastes which act as pasture lands, and the permanent pastures, which are locally called the *orans* (Raina and Joshi, 1994; Table 13). Maximum losses of available P and K were noticed in the wind-degraded cultivated fields (58% and 37%, respectively), while the loss of organic carbon was maximum in the degraded orans (50%).

Table 13. Effect of wind erosion on soil fertility in Jodhpur district

Nutrient	Cultivated land		Pasture land		Oran	
	Degraded by wind	Non-degraded	Degraded by wind	Non-degraded	Degraded by wind	Non-degraded
Organic carbon (%)	0.09	0.19	0.12	0.20	0.10	0.31
Available P (mg/kg)	2.80	3.60	4.10	6.40	2.35	9.60
Available K (mg/kg)	80.00	114.40	120.0	93.70	145.00	266.00

Indicators of Wind Erosion

Studies at CAZRI have indicated that a quick and reliable method for identification of mappable areas of wind erosion/deposition is careful observation of the morphology of present-day aeolian bedforms in the field and their signatures on remote sensing products (e.g. vertical aerial photographs, or false colour composites of satellite imagery), integration of the information with known climatic norms, and through inferences drawn about the complexities of air flow pattern, and hence of sand flow pattern under different geomorphic situations. Exposed plant roots, exposed calcretes in sandy plains, bowl shape of the cultivated fields, with high bounding fence-line sand ridges, are the clear markers of net erosion, while reactivation and extension of the stabilised sand dunes, formation of barchans, nebkhas and other smaller sand bodies like sand streaks provide the evidence of net deposition. Using such indicators a study in the Luni Development Block of Jodhpur district estimated that between 1958 and 1977 approximately 1990 ha of land was affected by wind erosion/deposition, and that another 18,000 ha land, mostly in the sandy undulating terrain, could be affected in 'near future' if the deep ploughing of dune slopes, overgrazing of sandy terrain and indiscriminate removal of trees and shrubs continued unabated (Singh *et al.*, 1978). Similar situations have been noticed in many other parts across the desert, including the naturally stabilized sandy landscapes in the wetter eastern part (e.g., Pushkar - Budha Pushkar lake area near Ajmer, parts of Sikar, Churu and Jhunjhunu districts). In some areas in the east even the accelerated fluvial processes are helping the aeolian processes. The sand dunes in these areas have greater stability due to higher rainfall, and have many rills and gullies along their slopes. Over-exploitation of the natural vegetation and cultivation pressure on these dunes are now causing the gullies to cut more vigorously into the sandy terrain, produce more loose sand and transport the material downstream to make it readily available to aeolian processes.

Field indicators

It has been possible to identify some field indicators of wind erosion and deposition in the different rainfall zones of the desert (modified after Singh *et al.*, 1992; Table 14).

Table 14. Field indicators for assessing wind erosion/ deposition in western Rajasthan

Terrain	Average rainfall (mm)	Major indicators for assessment	Severity
Flat sandy plains with dominantly loamy sand to sandy loam soil	100-550	Fresh sand sheet upto 30 cm thick; few scattered new fence line hummocks and nebkhas upto 100 cm high	Slight
Moderately sandy undulating plains and sand dunes with loamy sand soils; thickly sand sheeted plains	Above 300	Presence of reactivated fresh sand of 50 to 150 cm thickness on stable dunes, sandy plains and fence line hummocks; many recently formed nebkhas	Moderate
Moderately sandy undulating plains and sand dunes with sand to loamy sand soils	Below 300	Reactivated and fresh sandy hummocks (nebkhas) and sand ridges of 90-300 cm height; sand sheets of 60-150 cm thickness between undulations; reactivated stable dunes with fresh sand deposits of 70 to 200 cm thickness; exposed plant roots to a depth of 40 to 100 cm in the sandy plains indicate erosion	Moderate
Moderate to strongly undulating sandy plains with closely spaced hummocks and high sand dunes with sand to loamy sand soils	100-550	Closely spaced sandy hummocks and sand ridges of 1 to 4 m height with fresh sand cover; sand deposits of 100-300 cm thickness usually present between undulations; highly reactivated sand dunes are covered by fresh sand and superimposed by crescentic bedforms of 2 to 4 m height	Severe
Barchan dunes and very thick sandy plains with loose sand throughout the profile	100-550	Areas of drift sand, especially as fields of barchans of 2 to 5 m height, which encroach upon roads, settlements and agricultural fields; also areas with very closely spaced nebkhas of 2-5 m height	Very severe

Satellite image characters

Visual interpretation of the false colour composites (FCCs) of satellite imagery, especially the IRS LISS II images (36.5 m spatial resolution) of dry summer months (May-June), and varification of the interpreted units in field have led to identification of some typical image characteristics of wind erosion and deposition. Although these patterns were recognised in Jalor area (Raina *et al.*, 1991; Table 15), chances of their application potentials in other similar environments are high.

Table 15. Satellite FCC image characteristics of wind erosion/deposition features

Wind erosion/deposition feature	Signature on satellite FCC
Sand sheets and fence line hummocks	Uniform whitish or light pale brown colour
Fresh sand deposits on stable sand dunes	Reactivated sand in bright white.colour; stable dune surface in light yellow
Fresh sand deposits on closely spaced sandy undulations as sand ridges	Medium white tone, because of cultivation practices
Barchans	Bright white tone

The visual interpretation is, however, subjective. No two interpreter will, perhaps, agree to the severity of a degradation class, since value-based judgement is involved. Therefore, efforts have also been made to understand the digital image characteristics of wind erosion/deposition features. This was tried for the reactivated aeolian sand categories in the north-eastern fringe of the desert. The spectral response characteristics of the sand in different wavelength bands of Landsat MSS were processed using the following formulae:

$$0.43\ \text{band4} + 0.63\ \text{band5} + 0.59\ \text{band6} + 0.26\ \text{band7}.$$

Termed as Soil Brightness Index (SBI), it helped to reduce the effects of vegetation and highlighted the different categories of sand reactivation. However, the signatures of the salt-affected areas and the riverine sand got mixed up with the areas of highly reactivated aeolian sand, thus leading to some misrepresentation. Therefore, a density slicing was carried out on the SBI output, using available ground information. This helped to substantially reduce the errors in classes (Kar, 1996). It was possible to demarcate the areas of slight, moderate and severe degradation by wind. The salt-affected lands could be separated from the other classes because of their brighter values. The highly reactivated aeolian sand and the riverine sand, however, are difficult to separate everywhere. The inability of the system to differentiate between the thin and the thick covers of fresh sand also put some limitations to the mapping of severity classes.

Mapping of Wind Erosion

Spatial pattern of wind erosion

Using the field criteria and the satellite image characteristics mentioned above, it has been possible to map the phenomena of wind erosion/deposition at 1:1 million scale. The classes mapped are: very severe, severe, moderate, slight and negligible. Table 16 provides the area statistics for the different classes. According to it75.57 per cent area of the region is under slight to very severe categories, while the rest 24.43 per cent area is almost free of such hazard.

Table 16. Wind erosion/deposition classes in western Rajasthan

Erosion/deposition class	Area (km2)	Percentage of total area
Very severe	5800	2.78
Severe	25540	12.23
Moderate	73740	35.32
Slight	52690	25.24
Negligible	50981	24.43

Broadly, the extreme western part of Jaisalmer district, bordering Pakistan, is under very severe class, where large, elliptical fields of high megabarchanoids occur amidst linear dunefields, and where the wind erosivity index is greater than 480. Human settlement is almost absent in this zone, so that the activity can be related to natural processes only. This zone is flanked to the east by several southwest to northeast running belts of severe and moderate erosion/deposition classes that can be traced roughly up to Sanchor-Balotra-Jodhpur-Osian-Nagaur-Sikar-Jhunjhunu-Nohar-Suratgarh line in the east and north. The pattern almost replicates the erosivity pattern in the southern part, where the erosivity index is of moderate to severe categories. Large variation occurs in the northeast, especially in Ratangarh-Churu-Sikar area where the erosivity index is low, but high cultivation and grazing pressures on the highly erodible dune-interdune landscape has resulted in moderate to severe problems of wind erosion/deposition. In between the above zones the shallow sandy and rocky tracts of Barmer-Jaisalmer-Ramgarh-Pokaran are dominated by slight erosion/deposition, because of the paucity of sediments and hardness of the surface. Roughly to the east of Bhinmal-Jalor-Pali-Bilara-Merta-Nagaur the terrain consists mainly of sandy alluvial plains, with scattered hillocks and rocky pediments. These areas are without appreciable sand sheet cover, have lesser wind erosivity and erodibility indices, and hence, have negligible problem of wind erosion. The deep alluvial plains in the north, especially along the Ghaggar valley and around Ganganagar, as well as the hilly areas of the Aravallis in the north-east, especially around Khetri, Nim ka Thana, Palsana and Nawa, are also under negligible wind erosion class.

Complexity due to water erosion

Large parts of the areas undergoing slight to negligible wind erosion/deposition, especially in the eastern half of the desert, have a dominance of water erosion. Although water erosion is not the theme of discussion here, it is important to note that the fluvial and aeolian processes in the region are complementary to each other, in the sense that material for transport by water is largely made available from the wind-sorted sand, while the water-eroded sediments become available to the wind-driven processes for re-distribution. This is especially true for the areas where both the activities are noticed in good measure. Water erosion here takes place during the short periods of high-intensity rainfall. Since the soil is dominantly loose sandy, the erosion is not detachment-limited, but transport-limited. Much of *the transportation takes place as mud flow of concentrated run-off along shallow channels,* resulting in micro-fan features and cascades of sand deposits in the plains after the stream floods. Soil erosion under such situation is a complex phenomenon, and can hardly be explained by the Universal Soil Loss Equation, which is primarily used as a conservation planning tool on crop land:

$$A = R.K.L.S.C.P$$

where A is the mean annual soil loss, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor and P is the erosion control practice factor.

Water erosion in the desert may be estimated better through the Water Erosion Prediction Project (WEPP) watershed model, which is a process-based, continuous simulation model, built as an extension of the WEPP hillslope model. The model can accommodate spatial and temporal variabilities in topography, soil properties and land use conditions within small watersheds, and can identify zones of sediment deposition and erosion within permanent channels and ephemeral gullies. It can also account for the effects of backwater on sediment detachment, transport, and deposition within channels, represent variability in erosion and deposition due to agricultural management practices, and provide a better estimation of sediment yield from the watershed (Ascough *et al.*, 1995).

Recent Changes and Future Scenario

As has been mentioned earlier, present-day human activity has largely accentuated the wind erosion problem. The terrain in the region is dominantly sandy, and is therefore, inherently vulnerable to wind erosion. Although periods of climatic amelioration have tended to stabilise the landscape and helped in weak pedogenesis in the sandy soil, human activities on these soils have increased so much during the last few centuries, and especially during the last fifty years, that the meta-stable sediments are becoming loose again to the depth of ploughing, and becoming more susceptible to wind action. Dating of dune sediments in the western part of the desert has suggested that, at the century-scale, the rates of present human-induced mobility of sand dunes are higher than the geological rates by a factor 3 or more (Kar *et al.*, 1998). On the other hand, long-term trend for monsoon rainfall in western Rajasthan suggests a slight increase, in spite of the large inter-annual variations (Pant and Hingane, 1988). This increasing trend in rainfall should result in an increase in soil moisture and vegetation cover, and lead to some stabilizing effects on the aeolian sand. The effects may be more discernible in the low wind erosivity zone of the eastern part and in the moderate wind erosivity zone in the central part, provided the positive trends towards landscape stability are not offset by the human-induced acceleration of the aeolian processes. We shall discuss these trends with some examples.

Meteorological observations at CAZRI Research Farm, Jodhpur, reveal that the mean summer wind speed (May and June) at Jodhpur has gradually decreased from 1967 to 1998, although some years in between recorded higher mean wind velocities (e.g., 1969, 1973 and 1985; Fig. 7). Dust storm (*Kali-Pali Aandhi* in local perlance) have also declined in number over the same period (Fig. 8). In contrast the annual rainfall has shown an increasing trend (Fig. 9). Application of Mann-Kendall rank statistics to the data indicate that the decreasing trends for wind speed and dust storms are 'significant', but the increasing trend for rainfall is not. The trends may be a reflection of the climate amelioration suggested earlier by Pant and Hingane (1988), and it is quite likely that these changes have led to a slight decline in the potentials of wind erosion under natural conditions, at least in the eastern half of the desert.

The decadal changes in the spatial pattern of sand reactivation and vegetation cover in the dune-covered Shergarh-Chaba-Pareu area to the west of Jodhpur were studied with the Regional Remote Sensing Service Centre (RRSSC), Jodhpur. Digital remote sensing analysis techniques were employed on the satellite images of 15th February, 1975, and 5th January, 1992, to measure the 'soil brightness', which indicated the sand reactivation pattern, and also

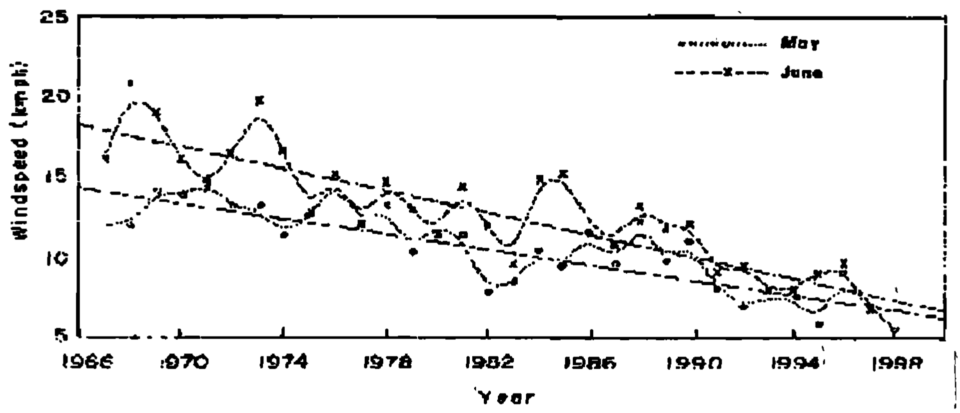

Fig. 7. Mean summer wind speed (May & June) at Jodhpur (1967-1998).

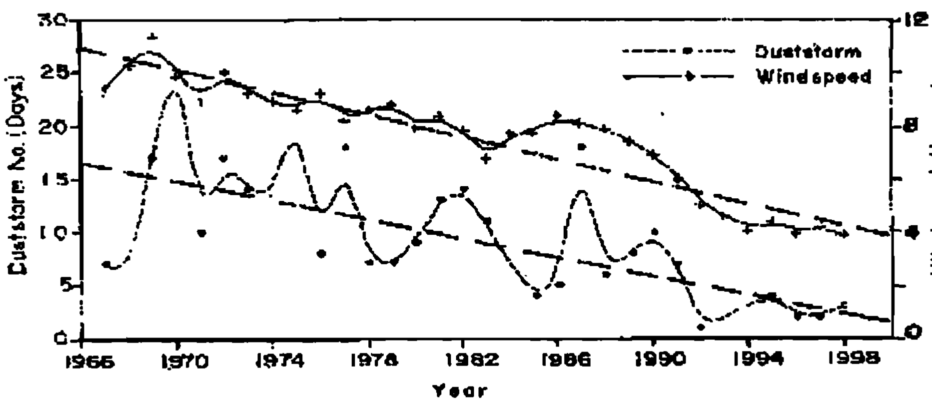

Fig. 8. Dust storm (annual) and mean annual wind speed at Jodhpur (1967-1998).

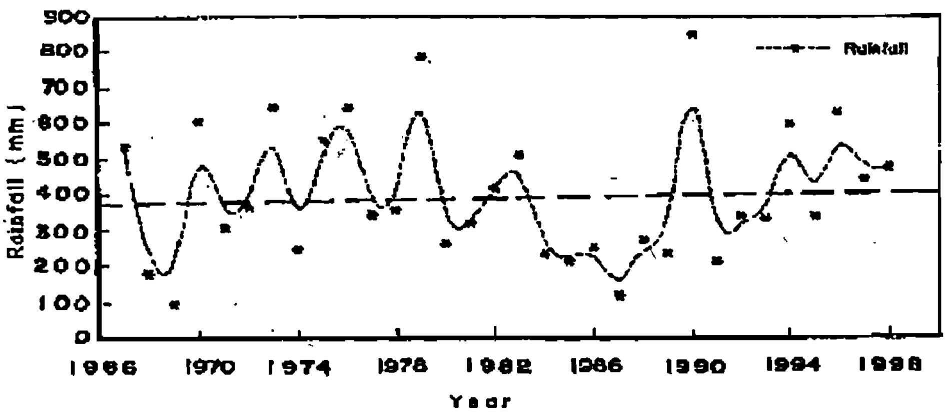

Fig. 9. Rainfall (annual) at Jodhpur (1967-1998).

to calculate Normalised Difference Vegetation Index (NDVI) for mapping the maximum green vegetation cover in the scenes. The results show a slight decline in the 'low' and 'high' sand reactivation categories, but not much variation in the moderate reactivation category (Table 17). The maximum green vegetation cover, on the other hand, increased during the same period (Table 18). These changes possibly reflect the recent changes in climate that have been mentioned above, and other factors like environmental awareness of the people and bringing some areas under winter cropping through well irrigation. However, the environmental conditions in the months before imaging might also have influenced the image patterns. The year 1974 was a drought year, when Jodhpur recorded an annual rainfall of 194.4 mm, against the long-term average of 368 mm. The contribution of monsoon rainfall was 174.4 mm. The values for 1991 were 232.5 mm (annual) and 209.0 mm (monsoon). At Shergarh the annual rainfall in 1974 was too meager, 42.0 mm only. Monsoon rainfall contributed 37.0 mm. In 1991 the annual rainfall was 204.0 mm and the monsoon contribution was 179.0 mm. The long-term average annual rainfall for the station is 252.4 mm.

Table 17. Sand reactivation in Shergarh-Chaba-Pareu area, 1975 and 1992

Month & Year	Area under sand reactivation categories					
	Low		Moderate		High	
	Km^2	% area	Km^2	% area	Km^2	% area
Feb., 1975	1277	78.1	220	13.4	139	8.5
Jan., 1992	1365	83.4	216	13.2	55	3.4

Table 18. Green vegetation cover in Shergarh-Chaba-Pareu area, 1975 and 1992

Month & Year	Area under vegetation cover categories			
	Maximum green		Others	
	Km^2	% area	Km^2	% area
Feb., 1975	1611	98.5	25	1.5
Jan., 1992	1570	96.0	66	4.0

The introduction of Indira Gandhi Canal network in the western part of the desert has resulted in dramatic changes in wind erosion scenario in the command areas within Ganganagar, Bikaner and Jaisalmer districts. During the initial years of canal construction in these moderate to very high wind erosivity zones large-scale sand mobility was noticed. When the water was introduced and irrigation of crop lands started in most of the sandy interdune plains, erosion was gradually reduced. The interdune plains were formerly put under dry farming of rainfed summer crops, or were kept as long fallow/ grazing land. Now these lands are under double cropping, using canal water. In order to reap better harvest from the land the farmers are using soil amendments which, together with the moist environment, has resulted in greater stability of the sandy surface, as has been noticed near Chattargarh, Jamsar, Pugal, Bajju and Nachna. Although parts of these areas are becoming affected by waterlogging and salinity, the wind erosion problem is much less than before. There is, however, greater danger of sand reactivation in the areas where low sandy hummocks and small dunes are being levelled to prepare the land for irrigated crops, but where the irrigation water is not very assured. Such cases have been noticed in isolated pockets in the tail end of the branch canals and minors, leading to a very fast development of barchans and other new dunes. Since large parts of the area lie in the high to very high wind erosivity zone, the danger of sand mobility is also very high.

Irrigation has also improved the landscape stability in the central and southern parts of the desert where large-scale exploitation of underground water from electrified wells has increased the area under winter crops. Many of the sandy plains in these areas are being irrigated thus. The crop residues and the root network of the harvested crops provide some stability to the land.

In contrast to such improvements in environmental conditions, cultivation pressure on the land is increasing, both in the irrigated and the non-irrigated areas. Tractor ploughing of the sandy soils in the eastern and central parts of the desert has increased tremendously during the last two decades. It is also spreading fast in the drier west. What is alarming is the use of tractors even on the middle and the upper slopes of high sand dunes. Such activities tend to nullify the stabilizing effects of increasing rainfall and declining wind speed, and accelerate the aeolian processes manifold. The problem is likely to be aggravated again by the decision of the government to distribute marginally suitable lands for agriculture, especially if it is not backed up by sound policies on land management.

Controlling the wind erosion/deposition over a large area is not an easy task. Researches at Central Arid Zone Research Institute have perfected many technologies which can be applied in the stabilization of sand dunes and in restraining sand movement from crop lands. The technologies are regularly transferred to the agencies and individuals who are engaged in sand control measures. However, large-scale sand control measures are difficult to apply, even at the Government level, because of the huge monetary and human resources needed for it. The 1:1 Million scale map on wind erosion, that forms a part of this bulletin, may be helpful in identification of the sectors that need prior attention of the planners and development agencies.

Summary and Conclusions

Wind erosion in western Rajasthan is primarily controlled by strong summer wind before the monsoon rainfall. Under natural set-up the spatial extent of wind erosion is predominantly determined by the erosivity of wind, as well as by the erodibility of soil by the wind. Since this is one of the most densely populated deserts of the world, where agriculture and livestock rearing are the major forms of occupation, the uses and abuses of land also contribute to wind erosion. Rainfall gradient from east to west and wind speed reduction from west to east have significant bearing on the spatial variation in wind erosivity. More than 60 per cent area of the region is covered with dune landscape and, hence, large areas are highly erodible to wind. Broadly, the drier western part of the desert is prone to very high wind erosion, while the wetter eastern part is less susceptible, except in the areas where the erodible sandy soils have been subjected to very high human and grazing pressures, leading to acceleration of the wind erosion processes. Pressures of cultivation and grazing are increasing steadily in the region, more so during the last fifty years when technological changes like use of tractors for deep ploughing of the sandy soils and even the slopes of stabilised sand dunes, have enormously increased the potentials of wind erosion. The need for increasing the areas under crops has also influenced wind erosion in recent decades. In contrast, the records suggest a slight increase in rainfall and drop in wind speed and dust storm activities, particularly in the eastern part. Canal irrigation has been introduced over large tracts, especially in the dry and more windy western part, where an increase in plant cover, along with the increased soil moisture, may lead to a significant drop in wind erosion, although large-scale levelling of sand dunes and sandy hummocks will increase the potentials of erosion, especially if the lands so transformed are not managed properly. Irrigation has also increased in the eastern and central parts of the region, especially using underground water. This has also influenced wind erosion. In other words, more complexities have been introduced in the wind erosion scenario by the changing land use practices. Considering these phenomena, the spatial pattern of wind erosion has been mapped into the categories of negligible, slight, moderate, severe and very severe erosion, using field data and interpretation of satellite images. About 60 per cent area is under slight to moderate wind erosion, while 15 per cent area is under severe erosion. The 1:1 million scale map on wind erosion may help the planners, land developers and community at large to fix the priority areas for control measures and sustainable development.

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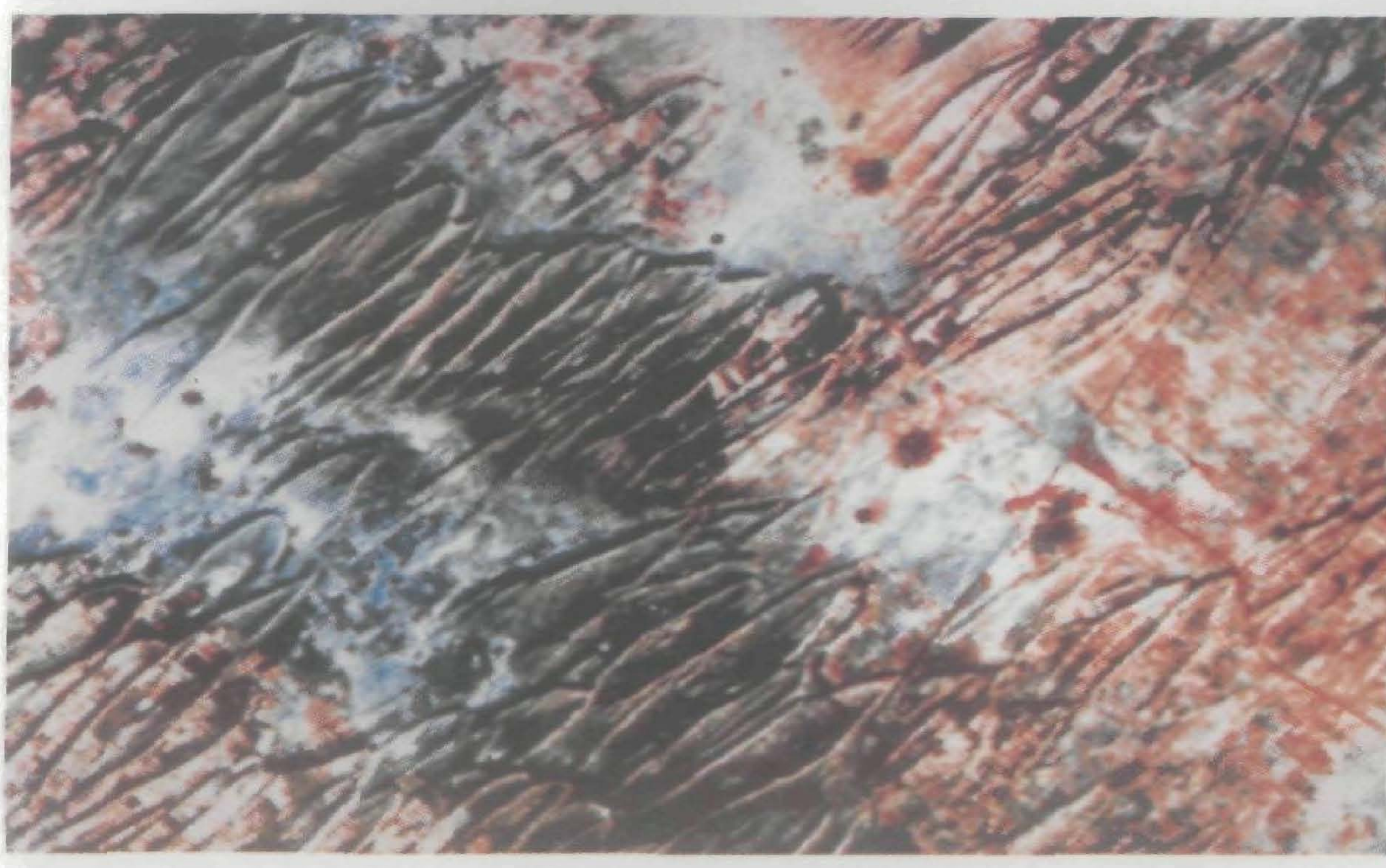
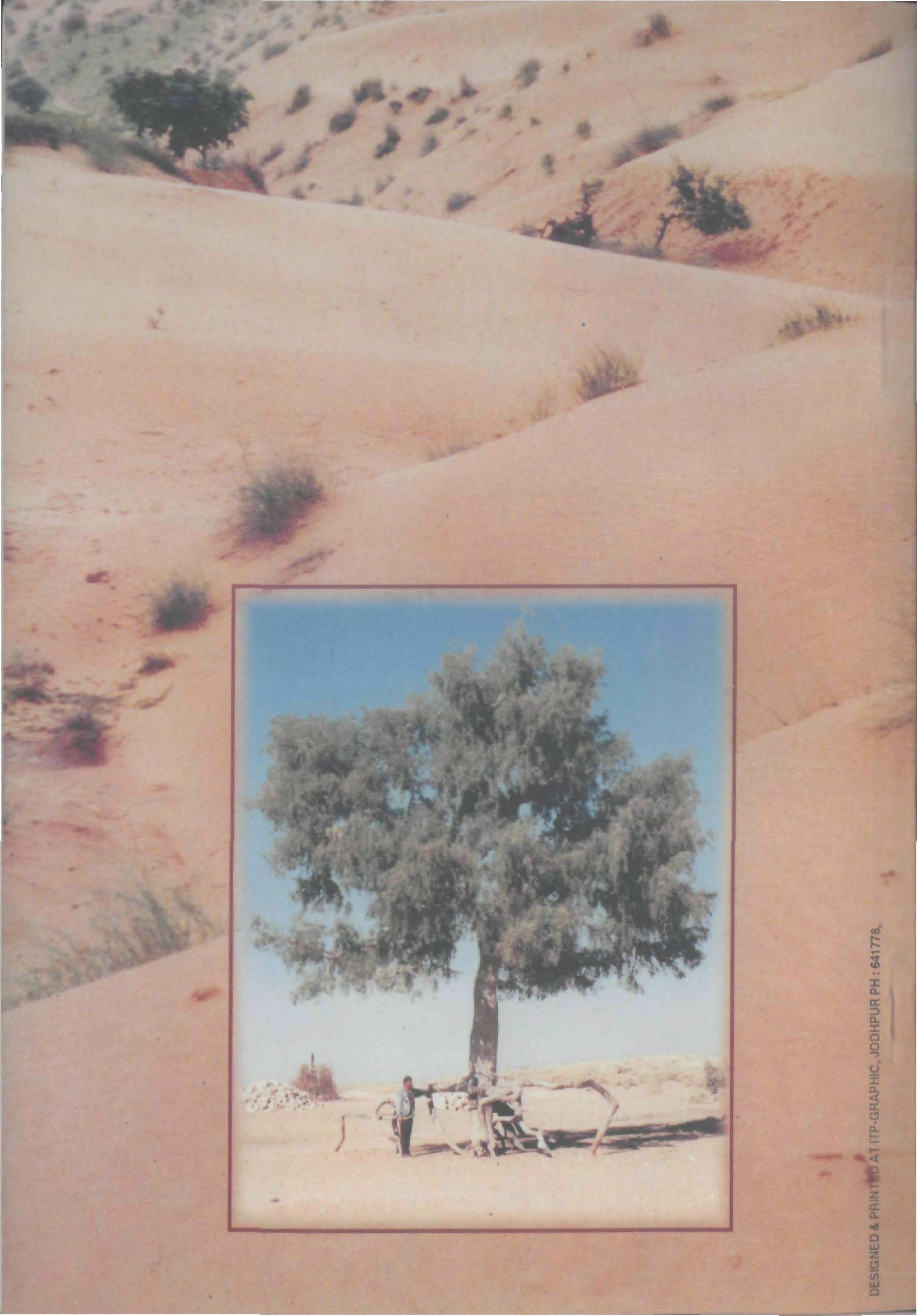
Description of photographs used in the bulletin

- Cover photographs show recent sand reactivation on the slopes of old sand dunes in Sikar area; inset on the back cover shows roots of a Khajri (*Prosopis cineraria*) tree near Chamu, exposed due to strong wind erosion.

- Inside back cover photographs show:
  - Pearl millet crop buried by low mobile dunes in Churu-Jhunjhunu area (top).
  - IRS-1C LISS-III FCC of Harsani area in Barmer district, showing recent sand deposition in the interdune plains and along dune slopes (bottom).





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