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ISO 9001 : 2008
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FOREWORD

Water resources are of vital importance in arid and semi-arid regions of the world, and conflicts over its access and possession are likely to worsen under the anticipated climate change scenario. Climate change due to enhanced greenhouse effect is likely to have an impact on agricultural, social, and economic systems. Rise in atmospheric temperature on account of global warming will affect the hydrological cycle, alter magnitude and distribution of rainfall, magnitude and timing of runoff, soil moisture availability, and groundwater levels. The frequency of extreme events such as droughts and floods are also likely to increase under the projected climate change scenarios. Changes in temperature and precipitation pattern will affect the evapotranspiration demands, and hence the irrigation water requirement.

Agriculture is one of the major water demanding sectors. In arid regions of Rajasthan, economy is primarily agricultural based and any shortage of water for agricultural use is likely to have cascading effect on various sectors of economy. A small perturbation in magnitude and frequency of rainfall, and resulting decrease in water availability may lead to drought like conditions in this region. Increased frequency and intensity of drought, especially in drought prone regions like Rajasthan, represent potentially the most serious impact of climate change on agriculture and allied sectors both at a regional and national level. Effective adaptation measures are needed to increase water use efficiency and reduce losses.

In view of limited irrigation resources in arid regions, participatory watershed management, supplemental irrigation, deficit irrigation, *in-situ* and ex-situ rainwater harvesting and recycling, use of poor quality water, conjunctive use of water, and pressurized irrigation have a very high potential to enhance water use efficiency, leading to improved water use and efficient use of other input resources like seed and fertilizer. Greater adoption of these approaches and technologies will certainly lead to efficient management of scarce water resources in arid and semi-arid regions of the country. Results of various experiments conducted in the hot arid zone of Rajasthan to improve water use efficiency have been compiled in this research bulletin. I compliment the authors for this work. I am confident that this bulletin will serve as a reference guide to various stakeholders involved in planning water saving interventions for climate resilient agriculture, including design and application of pressurized irrigation system.

(Alok K SIKKA)

September, 2014
New Delhi

PREFACE

Globally, the demand for water has been on the increase from all sectors viz., agriculture, industry or municipal use. The likely changes in climate due to global warming will further aggravate the demand of water for various enterprises. The agriculture sector is the largest consumer of water using almost 80% of the water and it continues to be the major sector in coming decades.Increasing the agricultural production level for feeding the world population with dwindling water resources is a challenge. The competition for freshwater often implies that water for irrigation is not always available in the required quantity and/or quality. Future projection is even worse considering factors viz., climate change, rapid urbanization, speedy industrialization and ever increasing population growth. The difficult situation can, however, be eased to a great extent by proper management of water including its conservation. Therefore, allocation of limited water supplies is central to irrigation management decisions. The conventional method of irrigation has been notefficient resulting in low water use efficiency besides creation of problems like waterlogging and salinity. Many countries have started employing efficient water distribution systems through pressurised irrigation. On account of its high irrigation efficiency, besides improving the yield and quality of the produce, this system has gained wide popularity over the years. Judicious use of water is vital to achieve higher productivity in a sustainable manner. Central Arid Zone Research Institute has developed several improved water management practices to enhance water use efficiency and productivity without affecting the soil health. Planting arrangements and other crop production technologies with pressurised irrigation have been developed. Agronomic measures, including planting arrangements and other crop production technologies, in conjunction with pressurised irrigation have been developed at the institute. The work of previous CAZRI workers included in the manuscript is duly acknowledged.

Anurag Saxena
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INTRODUCTION

Efficient use of water is a central issue throughout the world. Water, a finite source, is essential for both the human society and the ecological systems that humans rely on. With the population growth and economic development, water has become increasingly scarce in a growing number of countries and regions in the world. In spite of having the largest irrigated area in the world, India too has started facing severe water scarcity in different regions. Owing to various reasons the demand for water for different purposes has been continuously increasing in India, but the potential water available for future use has been declining at a faster rate. The agricultural sector (irrigation), which currently consumes over 80% of the available water in India, continues to be the major water-consuming sector due to the intensification of agriculture. Though India has the largest irrigated area in the world, the coverage of irrigation is only about 40% of the gross cropped area as of today. One of the main reasons for the low coverage of irrigation is the predominant use of flood method of irrigation (conventional), where water use efficiency (WUE) is very low due to various reasons. Available estimates indicate that WUE under flood method of irrigation is only about 35% to 40% because of huge conveyance and distribution losses. This requires an increase in water productivity (WP) and WUE. It is much more pertinent for a vast tropical country like India, which experiences extreme variation in climate and rainfall. India, though achieved self-sufficiency in food with the help of efficient management of her natural resources leading to green revolution but arid and semi-arid regions are still lagging behind. It is necessary to economize the use of water and at the same time increase the productivity per unit area and per unit quantity of water.

Arid regions are encountered by various problems. Harsh climatic conditions in arid regions allow the farmers to grow only one crop during rainy season that too depend on the rainfall. The average annual rainfall of western arid region is 317 mm. The rainfall is highly variable and erratic with frequent drought spells. The number of rainy days varies from 10 to 25. Groundwater is very deep, saline at many places and expensive to use. Indiscriminate use of water on undulating highly permeable sandy soils through conventional irrigation resulted in fall of groundwater by 0.6-1.0 m annually. The situation of over exploitation of groundwater is more serious in the region where out of 11 districts, 6 are in category of over exploited and remaining 5 are in category of semi critical zone. Rainfed farming is adversely affected by low and erratic rainfall coupled with high evaporative demand and low moisture retention by light textured soils. On the other hand indiscriminate use of scarce water through conventional irrigation management practices led to exhaustion of ground water resources and development of water logging in canal command area. Hence, conservation and efficient management of limited water is the need of the hour for achieving sustainable production for longer period on light textured soils of arid and semi-arid regions. Under climate threat water demand will be more.

Studies on global warming and its effect on climate change are being pursed vigorously as a multi-disciplinary problem. Global warming due to enhanced greenhouse effect is expected to cause major changes in various climatic variables like absolute humidity, precipitation, and net terrestrial and global solar radiation etc. Atmospheric temperature is probably the most widely used indicator of climate changes, both on global and regional scale. Global temperature has increased by 0.3 to 0.6°C since the late 19th century and by 0.2°C to 0.3°C over last 40 years. In last 140 years, the 1990s were the warmest period (Jones and Briffa, 1992). In Indian context, Hingane *et al*. (1985) reported an increase in mean annual temperature by 0.4°C per 100 years during the 20th century. However, increasing temperature trend is not valid over entire country. Kothawale *et al.* (2002) reported a rise of 0.5°C in mean annual temperature over last century. However, no systematic change in mean minimum temperature was observed. The pattern of spatial and temporal changes in climatic variables due to global warming is a matter of much debate and studies are increasingly going on worldwide (Chattopadhya and Hulme, 1977; Georgiadi *et al.,* 1991; Muhs *et al.,* 1993; Iglesias *et al.,* 1994; McNulty *et al.,* 1997; Feddema, 1999). As a consequence of climate changes, a significant impact on hydrological parameters viz. runoff, evapotranspiration, soil moisture, ground water etc. is expected (Nemec and Schaake, 1992; Gleick, 1986; Bultot *et al.,* 1988). Evapotranspiration (ET) is the major component of hydrological cycle after precipitation and determines the crop water requirement. The principle factors that influence the crop water requirement (or ET) depend upon several climatic parameters viz. rainfall, temperature, humidity, sunshine hours etc. Any change in climatic parameters due to global warming will also affect evapotranspiration or crop water requirement. Eventual global warming would increase dry conditions in the world's arid regions by increasing potential evapotranspiration, aggravating the processes of desertification in conjunction with the ever-growing impact of man and domestic animals on fragile and unstable ecosystems (Houerou *et al.,* 1993). Mahmood (1997) reported a 5% increase and a 4% decrease in seasonal total evapotranspiration occurs under each 1°C warmer and cooler air temperature conditions, respectively.

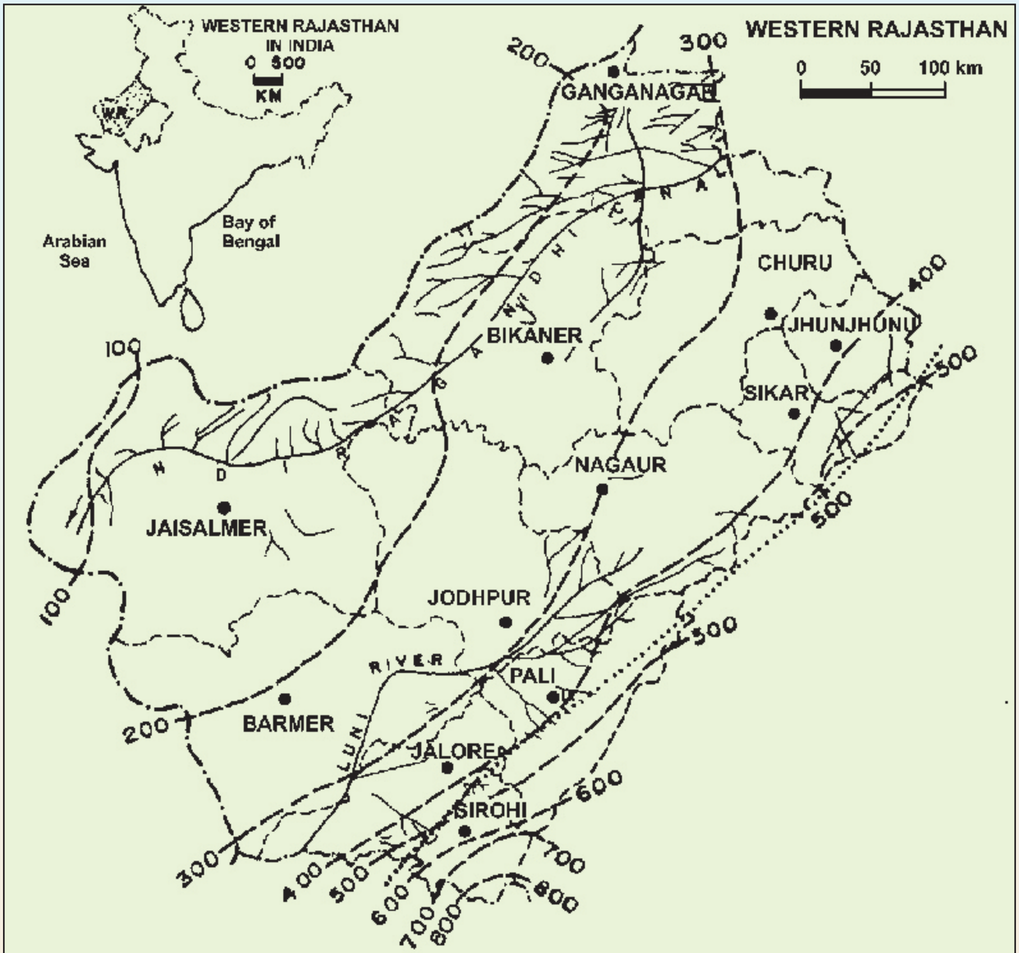
So, for future crop planning and management of water resources knowing expected change in evapotranspiration will be prerequisite. Following the approach of Martin *et al.* (1989) and Rosenberg *et al.* (1989) an attempt was made to understand the sensitivity of evapotranspiration for the expected change in climate due the global warming for arid region of Rajasthan (India).

WESTERN RAJASTHAN AND ITS CLIMATE

The Indian hot arid region occurs between 22°30' and 32°05' N latitudes and from 68°05' to 75°45' E longitudes, covering western part of Rajasthan (19.6 Mha, 69%), north-western Gujarat (6.22 Mha, 21%) and south-western part of Haryana and Punjab (2.75 Mha, 10%). The majority of the hot arid zone comes under northern-western part of Rajasthan covering 12 districts. Rainfall distribution in the region is highly uneven over space and time (CV>60%). The region receives low rainfall (<100 mm to 500 mm), has high evapotranspiration and high temperature regime (Fig. 1). Groundwater is deep and often brackish. The western-central area is devoid of drainage system and surface water resources are meagre. Due to low and erratic rainfall, replenishment of water resources is also very poor. With vast variations in rainfall and ground water availability, the differences in access/availability of water is also apparent i.e. while the Rajasthan state overall average annual rainfall is 531 mm; it is 318 mm for the western parts of Rajasthan. As such the whole Rajasthan state is being categorized as the driest and water scarce (having per capita water availability below 1000 m^3 $year^{-1}$) state since 1991 in the country (Narain *et al*., 2006). Increasing pollution by big and small industrial units, unregulated mining and even over-extraction of water from deep wells also add to the water quality problem in major areas. Rapid urbanization and industrialization make such availability of water due to increase in evapotranspiration demand existing differences even more glaring. Under scenario of water scarcity any reduction in water availability caused by global warming will seriously affect the agricultural and industrial growth.

EVAPOTRANSPIRATION V/S TOTAL WATER DEMAND

About 84% of the total population of Rajasthan lives in rural areas and 78% of the rural population depends on agriculture. Out of total available surface and groundwater, major portion (>85%) of it is being used for the agriculture. Table 1 presents projected water demand of Rajasthan for various sectors.



Mean annual rainfall, mm (– –), stream characteristics (—) and Eastern boundary (··········) of arid zone of Rajasthan

Fig. 1. Western Rajasthan- Physiography.

Table 1. Projected sectoral water demand for Rajasthan (Billion cubic meter)

Purpose/Year	2005	2015	2045
Domestic	2.6 (6.5%)*	3.2 (7.1%)	4.7 (8.2%)
Livestock	0.9 (2.2%)	1.1 (2.4%)	1.3 (2.3%)
Irrigation	35.9 (89.5%)	40 (88.7%)	49.1 (86.0%)
Others	0.7 (1.7%)	0.8 (1.8%)	2 (3.5%)
Total	40.1	45.1	57.1

* Figures in parenthesis indicate % of total water demand; Source: Report of Expert Committee on Integrated Development of Water Resources, Government of Rajasthan, June 2005.

Agriculture continues to be the major sector of water demand even in coming 4 decades. Water as such and also as carrier of large amount of nutrients is required in a large measure for the successful growth of the plants. The metabolic activity of cells and plants is closely related to their water content. The total quantity of water required by different crops/plants for the essential physiological functions is less than 1% of the total water absorbed. Most of the water entering the plant is lost in transpiration and evaporation from the soil surface. However, failure to replace the water lost by plant in transpiration and evaporation from soil surface results in the loss of turgidity, cessation of growth and eventual death of plant from dehydration. Hence, for successful crop production evaporation demand of soil surface and transpiration demand of plant/crop must be satisfied. So to meet the evapotranspiration demand, about 84-85% of total water resources are being used. Thus, evapotranspiration demand has direct bearing on the total water demand.

GLOBAL WARMING AND EVAPOTRANSPIRATION

To study the effect of global warming on evapotranspiration (ET), knowledge of the predictions/forecasts for the likely change in climate parameters is prerequisite. In Indian context, a warming trend of 0.57°C per 100 years is broadly consistent with the observed global warming over last century (Pant and Kumar, 1997). However, the precise forecast for the overall spatial and temporal changes in climate due to global warming is not available. Presently no global tool or model is available to predict magnitude of likely changes in climatic parameters due to global warming for a region/place specific. Under such circumstances, the effect of global warming in a particular region can only be studied in terms of likely changes in certain climate parameters. The most visible sign of climate change is rise in temperature affecting ET primarily by increasing the capacity of air to hold water vapour. Decreased cloudiness and increased solar radiation would increase ET. Saturation pressure increases exponentially with increase in temperature. If all other factors remain unchanged, warming would cause drier air and hence more ET. In the present study temperature has been raised by 1° to 2°C keeping other parameters constants and its effects were studied on total evapotranspiration demands for the western Rajasthan.

ESTIMATION OF EVAPOTRANSPIRATION

For estimation of evapotranspiration FAO recommended Penman-Monteith model has been used. The recommended method is said to overcome shortcomings of the previous FAO Penman method and provides results that are more consistent. About 30 years (1979-2009) climatic data of 12 districts of western Rajasthan has been used for the study. To decrease the discreteness of climatic parameters, weekly averages over different years were used for estimation of evapotranspiration. According to Penman-Monteith combination equation, ET_o can be expressed as

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad \text{..........(1)}$$

where,

ET_o = reference evapotranspiration (mm day^{-1})

R_n = net radiation at the crop surface (MJ m^{-2} day^{-1})

G = soil heat flux density (MJ m^{-2} day^{-1})

T = mean daily temperature at 2 m height (^oC)

u_2 = wind speed at 2 m height (m s^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

e_s-e_a = saturation vapor pressure deficit (kPa)

Δ = slope of vapor pressure curve (kPa$^oC^{-1}$)

γ = psychrometric constant (kPa$^oC^{-1}$) = 0.665 x 10^{-3}.P

where, P is atmospheric pressure (kPa). P can be calculated by following equation

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad \text{(z is elevation above sea level (m))} \qquad \text{.......... (2)}$$

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \qquad \text{.......... (3)}$$

$$e^o(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right] \qquad \text{.......... (4)}$$

$$\frac{4098\ \ 0.6108\ \exp\ \frac{17.27\,T}{T\ \ \ 237.3}}{T\ \ \ 237.3^{\ 2}} \qquad \text{.......... (5)}$$

Δ = Slope of saturation vapour pressure curve at air temperature T (kPa°C^{-1})

T = air temperature (°C)

exp {..} = 2.7183 (base of natural logarithm) raised to power {..}

The slope of the vapor pressure curve is calculated using mean air temperature (°C).

$$e_a \quad \frac{e^o(T_{min})\frac{RH_{max}}{100} \quad e^\circ(T_{max})\frac{RH_{min}}{100}}{2} \qquad \text{..........(6)}$$

$$R_n = Rns - R_{nl} \qquad \text{.......... (7)}$$

R_{ns} = (1-). R_s , = 0.23 for the hypothetical grass reference

$$R_s \quad 0.25 \quad 0.50\frac{n}{N}\ R_a \qquad \text{.......... (8)}$$

Where 'n' is actual duration of sunshine hours. The values of N and R_a can be obtained from standard Tables (Allen *et.al* 1998) for different latitudes and months.

$$R_{nl} \quad \sigma\ \frac{T_{max},K^4 \quad T_{min},K^4}{2}\ (0.34 \quad 0.14\sqrt{e_a})\ 1.35\frac{R_s}{R_{so}} \quad 0.35 \qquad \text{..........(9)}$$

where,

R_{nl} = net outgoing long wave radiation (MJ m^{-2} day^{-1})

σ = Stefan-Boltzmann constant (4.903 10^{-9} MJK^{-4} m^{-2} day^{-1})

T_{max}, K = maximum absolute temperature during the 24-hour period (K=°C+273.16)

T_{min}, K = minimum absolute temperature during the 24-hour period (K=°C+273.16)

e_a = actual vapour pressure (kPa)

R_s/R_{so} = relative short-wave radiation

R_s = measured or calculated solar radiation (MJ m^{-2} day^{-1})

R_{so} = (0.75 + 2 10^{-5}z) R_a

z = station elevation above sea level (m)

G = Soil heat flux, for period of day or ten-day soil heat flux beneath grass reference surface is relatively small or G= 0 (MJ m^{-2} day^{-1})

Weekly average long term meteorological parameters of 40 years (1971-2010) have been used as reference point of study as it accommodate all typical features of arid zone including droughts and good rainfall years of the arid zone. 40 years average annual rainfall of the region is 361 mm with 10-15 rainy days in a year. The coefficient of variation of rainfall varies between 40 to 70%. Observed data of temperature, humidity, sunshine hours and wind speed at two meter height has been used for the study. To smooth out sharp variation in climatic parameters, weekly averages were used in the analysis. Maximum possible sunshine hours (N) and radiation (R_a) have been interpolated for given latitude and time from the standard tables. Psychrometric constant (γ) depends upon atmospheric pressure which in turn depends on altitude. It was estimated as 0.065861 using Eq. 2.

IMPLICATIONS FOR WATER RESOURCES

Weekly reference evapotranspiration was calculated using above described Penman-Monteith equation. Sensitivity of ET has been studied by varying temperature within a range as described earlier while keeping other parameters constant. The normal average annual evapotranspiration of the western Rajasthan varied from 1502 mm for Nagaur to 2177.2 mm for Barmer (Fig. 2). According to Irving (1993) the greatest certain threat from climatic changes is by increase in evaporative losses and water demands caused by higher temperature. Globally evapotranspiration trends are projected for +5% to +10% increase due to increase in temperature by +2 to +5°C (Schneider *et al.,* 1990). Wetherald and Manabe (1981) found that global evaporation changes by 3% when temperature changes by 1°C. Similarly, Budyko (1982) suggests a 5% increase in evapotranspiration demand for each degree Celsius rise in temperature.

Table 2 presents the future scenario of annual evapotranspiration demand in response to expected change in temperature. As small as 1°C increase in normal temperature will enhance the evapotranspiration from minimum of 35 mm for Ganganagar to highest of 96 mm for Jaisalmer. Enhanced evapotranspiration would be primarily a consequence of higher air and land surface temperature.

The increase in evapotranspiration demand will have a direct bearing on total water demand for irrigation. The increase in temperature by 1°C will cause an additional annual water demand of 1570.9 mcm for the entire western Rajasthan based on net irrigated area of 3164512 ha (Table 3).

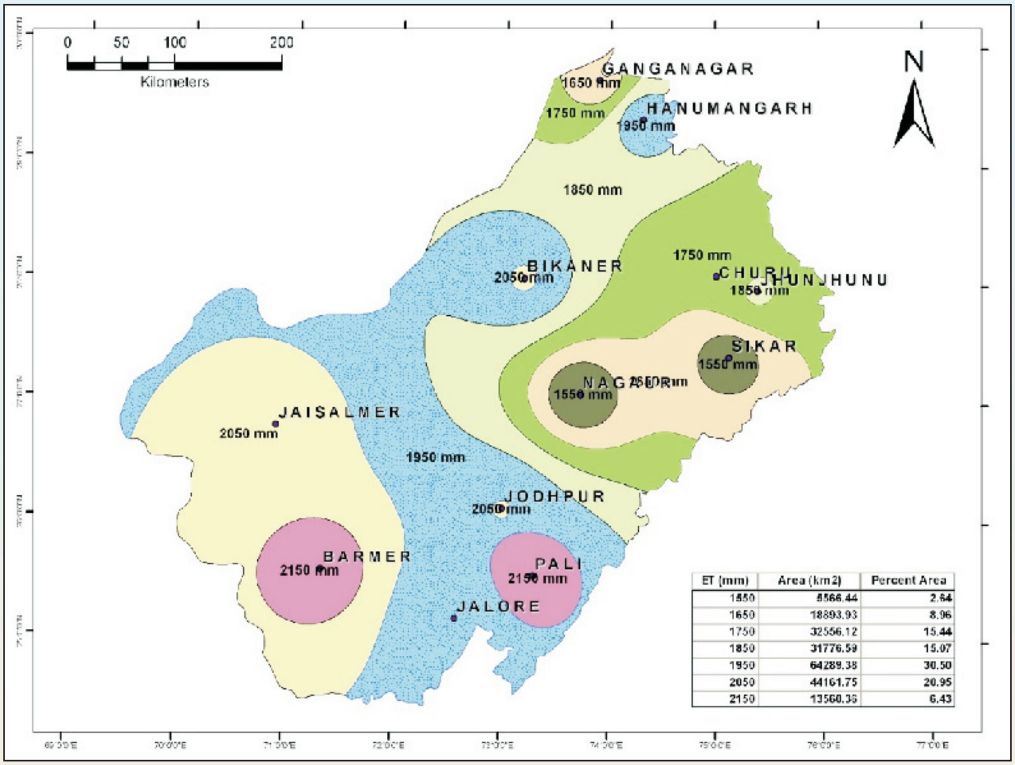


Fig. 2. Spatial distribution of evapotranspiration demand over western Rajasthan.

Table 2. Evapotranspiration demand under Global warming

District	**Evapotranspiration (mm)**				
	Normal	**+ 1°C rise in temp.**	**Net increase in ET (mm)**	**+ 2°C rise in temp.**	**Net increase in ET (mm)**
Barmer	2177.2	2224.9	47.7	2272.7	95.5
Bikaner	2009.7	2055.0	45.3	2100.5	90.8
Churu	1702.2	1737.4	35.2	1772.8	70.6
Ganganagar	1632.4	1667.5	35.1	1702.8	70.4
Hanumangarh	1973.4	2018.2	44.8	2063.0	89.6
Jaisalmer	2064.0	2160.0	96.0	2256.0	192.0
Jalor	1905.0	1970.0	65.0	2040.0	135.0
Jhunjhunu	1819.0	1883.0	64.0	1950.0	131.0
Jodhpur	2002.0	2045.8	43.8	2089.9	87.9
Nagaur	1502.0	1583.0	81.0	1669.0	167.0
Pali	2071.6	2117.4	45.8	2163.5	91.9
Sikar	1528.0	1569.0	41.0	1611.0	83.0

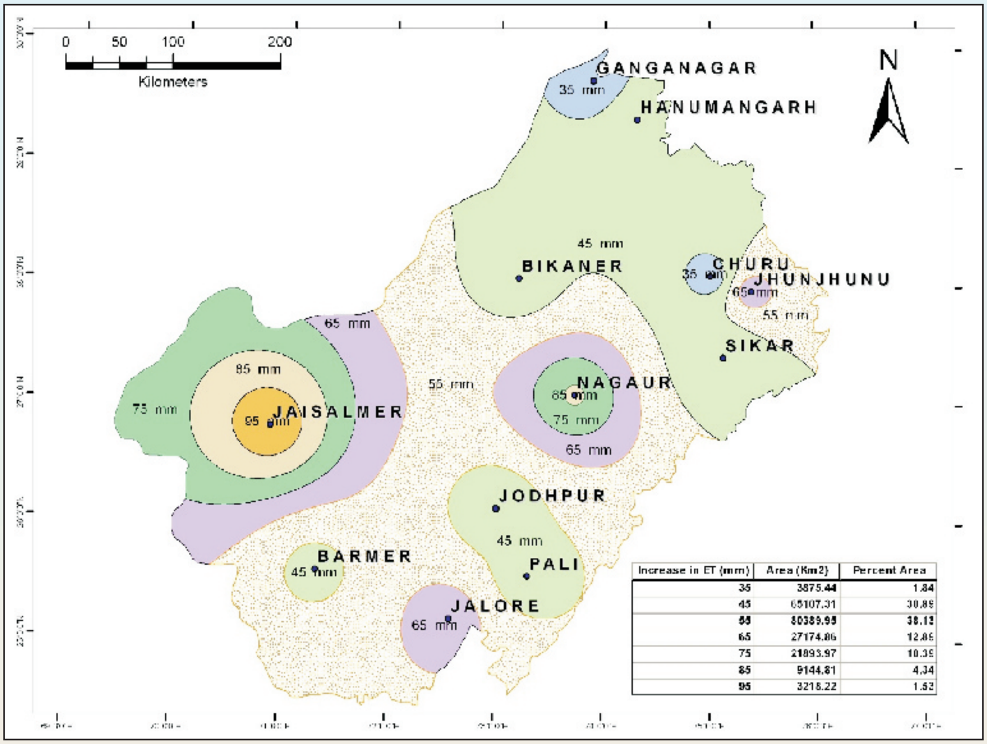
Table 3. Additional water requirement for irrigation under global warming by 1°C in western Rajasthan

District	Total area (ha)	Total cropped area (ha)	Total irrigated area (ha)	Net annual groundwater availability (mcm)	Additional water requirement for irrigation (mcm) (+1°C)
Barmer	2817332	1650376	150540	249.8049	71.81
Bikaner	3035589	1465305	228355	197.6075	103.44
Churu	1385889	1140803	58115	197.6883	20.46
Ganganagar	1092960	906759	786859	198.8341	276.19
Hanumangarh	970315	882697	549853	194.6094	246.33
Jaisalmer	3839154	467391	90745	52.5923	87.12
Jalor	1056602	740878	202153	423.6140	131.40
Jhunjhunu	591682	609659	242584	243.0369	155.25
Jodhpur	2256405	1227843	176571	393.1304	77.34
Nagaur	1764383	1365402	294800	628.1586	238.79
Pali	1233079	582884	112059	413.3910	51.32
Sikar	774244	671578	271878	324.5240	111.47
Total	20817634	11711575	3164512	3516.9914	1570.92

The total available utilizable ground water for western Rajasthan is 3516.9 mcm and increase of 1% in temperature will put additional stress of 44% on existing groundwater resources based on present land use pattern (Fig. 3).

Since western Rajasthan is not blessed with good perennial river systems, so any increase in water demand require careful planning for future water resource development. More emphasis is needed to develop technologies for reducing water losses in reservoirs, conservation of rainwater and development of such crop varieties that require less water. So it is high time for the planners/users/water resources managers to think in term of expected water demand due to global warming and its likely effect on water resources of Rajasthan. The availability of water has direct bearing on the type of crops to be grown and will determine the economy of the state.

The basic intrinsic characteristic of water dynamics in soil cannot be altered to a large degree but availability can be modified enormously by water conservation and water management practices. During the complete life cycle of a plant the most dynamic property is water content in soil. Since water that is conserved or supplemented becomes available to the plant through the soil, monitoring of water content under field condition is of paramount importance. The whole life cycle of plant revolves around extraction of water from the soil through its root network and transpiring through the



Increase in ET (mm)	Area (Km2)	Percent Area
35	3875.44	1.84
45	65107.31	30.89
55	80389.95	38.13
65	27174.86	12.89
75	21893.97	10.39
85	9144.81	4.34
95	3218.22	1.53

Fig. 3. Spatial distribution increased evapotranspiration demand under 1oC rise in temperature.

leaves in response to evaporation demand set up by the atmosphere. Any shortage of water in the soil is ultimately reflected by the growth of the plants in some form or another. Increasing water supply available to plants or enhancing water use relative to other losses and making efficient use of limited water are the three major concepts in optimizing water use in agriculture.

INCREASING WATER AVAILABILITY TO CROP PLANTS

Since rainfall is low and erratic efforts are needed to enhance the total water supply available to crops. Some of these include tillage, mulching, soil moisture barrier, contour bunding and *in-situ* water harvesting. Mechanical structures like contour bunding, terracing are the pre-requisite for water conservation on sloppy agricultural lands. Off-season tillage on alfisols helped in controlling weeds and conserving water. Such practice on arid soils may lead to soil erosion. Hence, minimum tillage was found to control 73% weeds and 43% increase in yield. Use of weed mulch increased the water availability to crops by restricting evaporation directly from soil surface.

CROP PLANNING BASED ON RAINFALL AND MOISTURE AVAILABILITY PERIOD

In dryland areas crop production depends on amount and distribution of rainfall. Most of the farmers still grow long duration traditional varieties under conventional practices. The productivity of these crops varieties is affected due to uncertain rainfall. Hence, there is need to develop short duration varieties, crop plan and agronomic practices matching to rainfall pattern. On the basis of climatic data all over India, suitable crops and varieties for early, normal and late onset of monsoon, improved inter cropping, time of sowing and agronomic practices have been identified and developed. In arid part of Rajasthan short duration varieties of pearl millet, clusterbean, moth bean, mung bean and sesame have been developed to minimize the risk of crop failure. With the early onset of monsoon, pearl millet and sesame get preference. While with the late onset of monsoon clusterbean, mung bean and moth bean get preference. Since the moisture evaporates very fast, it is suggested to complete the sowing immediately after rains.

All operations carried out in the field, from land preparation to crop harvesting, with the aim of increasing the crop yield are included under agronomical practices. Certain simple agronomical practices like optimum tillage, administration of organic manure and suitable cropping pattern are effective in retaining soil fertility as well as giving satisfactory crop yield.

Tillage Operation

Tillage makes soil loose and hence prone to erosion. Timing and depth of tillage are the two important factors which need special attention. Tillage should be done immediately before the crop season to take advantage of one or two early showers for land preparation. In arid region, land tilled into ridges and furrows across the wind direction has been found to reduce the effects of wind erosion during the summer months. Deep tillage improved the soil moisture storage, water use efficiency and grain yield of pearl millet (Saxena *et al*., 1997).

Land Levelling

Farm lands should be levelled for efficient management of water. Level lands allow more infiltration, thus increasing soil moisture and leaching. This in turn reduces run-off and hence soil erosion. Levelling of irregular land is done by the cut and fill method. Soil from the elevated portions is removed and placed in the depressed portions to obtain a level land.

Mulching

Mulching of open land surface is achieved by spreading stubble, trash or any other vegetation. The objectives of mulching are to minimize splash influence of rain drops on base surface, reduce evaporation, increase absorption of the rainfall, obstruct surface flow thereby retarding erosion and allow microbiological changes to occur at optimum temperature. Studies conducted at CAZRI showed that mulch application improved the water use and water use efficiency in pearl millet (Table 4).

Table 4. Mulching improves yield and WUE of pearl millet

Mulch	Water Use (ET) mm	Yield ($kg\ ha^{-1}$)	WUE ($kg\ ha^{-1}\ mm^{-1}$)
Polyethylene	279	2900	10.4
Bajra husk	269	2300	8.5
No mulch	291	1740	6.0

INCREASING WATER USE RELATIVE TO OTHER LOSSES

Evaporation of water directly from soil surface is an important component of the total water use of crops. Evaporation constitutes 19-46% of the total water on vertisols, 21% on alfisols and 12-18% on loamy sand soils. The best opportunity for water saving lies in methods increasing transpiration relative to other losses from the soil surface due to canopy shading. The elimination of weeds, optimum plant population and spacing and application of fertilizer/manure helped in better canopy growth and higher WUE of crops. Generally close row spacing and higher plant population is recommended in high rainfall areas or irrigated condition, but in arid region wide row spacing and low population is recommended. Paired row planting system helps in better canopy growth and hence evaporation from soil surface is restricted. Weeding improved the pearl millet yield by 44% over weedy condition (Table 5) in low rainfall season.

Table 5. Weeding enhances WUE ($kg\ ha^{-1}\ mm^{-1}$) and yield ($kg\ ha^{-1}$) of pearl millet

Treatment	Good rainfall (548 mm)		Low rainfall (252 mm)	
	Yield	WUE	Yield	WUE
Weedy	1672	3.1	1053	4.2
Weed free	1868	3.4	1521	6.0

MANAGEMENT OF LIMITED IRRIGATION WATER

In arid region water is limited and land is vast, hence water management should aim to maximize production per unit of water rather per unit of land. Some of the technologies like extensive, deficit and pressurized irrigation have been developed to maximize the production in arid region.

Extensive Irrigation

Extensive irrigation approach seeks to apply a small quantity of water over a large area rather large quantity of water over a small area. Production per unit land may decrease but production per unit water may increase. Wheat and mustard required 840 and 250 mm water per hectare to produce maximum yield. When the same water applied optimally in 3, 1.5 and 4.0 ha land in wheat and mustard, respectively gave less production per unit of land but total productivity per unit of water was more by bringing larger area under irrigation (Table 6). Singh (1997) observed that under given water supply the area brought under irrigation in pearl millet was more in subnormal rainfall years than low rainfall years, however, the production enhanced in both the situation by bringing larger area under irrigation in pearl millet (Table 7).

Table 6. Extensive irrigation maximise production for given water supply

Crop	Water use (mm)	Area (ha)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})
Wheat	840	1	5500	6.5
		3	9100	10.8
Mustard	250	1	1100	4.4
		1.5	2000	8.0

Deficit Irrigation

Deficit irrigation approach seeks to avoid irrigation at less critical stages of crop growth and apply less water at the end so as to eliminate water stored at harvest. One has to well verse with the crop growth stages less sensitive to moisture stress and proper balancing between water given and ET demand of crop.

Table 7. Increased area under S-IRR enhances pearl millet production

Good rainfall (331 mm)			Medium rainfall (266 mm)			Low rainfall (173 mm)		
S-IRR	Area	Yield	S-IRR	Area	Yield	S-IRR	Area	Yield
190	1.0	3660	292	1	3620	341	1.0	3540
76	2.5	7225	145	2	5380	209	1.6	4528
38	5.0	12950	73	4	7560	117	2.9	5829
0	1.0	2280	0	1	1400	0	1.0	1080

S-IRR = Supplemental irrigation (mm ha^{-1}), Area in ha, Yield in kg ha^{-1}.

RAINWATER MANAGEMENT

In arid and semi-arid parts experiencing rainfall from 150-350 mm and 350-550 mm respectively, rainfall is not sufficient to ensure a good crop. Crop production is adversely affected due to low and erratic distribution. In dryland farming, the solution to soil moisture problem lies in the storage of rainfall in the potential root zone of the soil by the water harvesting methods. Therefore, water harvesting would be an alternative to leave land fallow for increasing the available water supply for plant growth. In last two decades researchers and planners have given a lot of attention to dryland farming in such areas and for various regions specific agro-techniques have been evolved.

In-situ Rainwater Conservation: Water Stored in Soil Profile Itself

Interplot water harvesting: In many arid areas, water harvesting is used to increase the total water supply available to crops. It is practiced in variety of ways depending upon topography, soil and rainfall. Inter-plot water harvesting that uses a portion of land with 5% slope as catchment to generate runoff and divert it to adjacent area was found highly beneficial to improve the yield of many crops. CAZRI has developed water harvesting technique with 3 m cropped area and 1.5 m catchment area (catchment to crop area ratio = 0.5) with 5% slope on both sides (Fig. 4). Response of pearl millet to water harvesting system was studied at CAZRI. Crop water supply, over the check, ranged from 23 to 60 mm in the extremely dry season and 108 to 286 mm in the season with a good rainfall. As a result, in water harvesting plot a yield of 3717 kg ha^{-1} was obtained with 69% of normal rainfall. This ratio (0.5) was found optimum for the type of soil, climate, and surface sealing pond sediment.

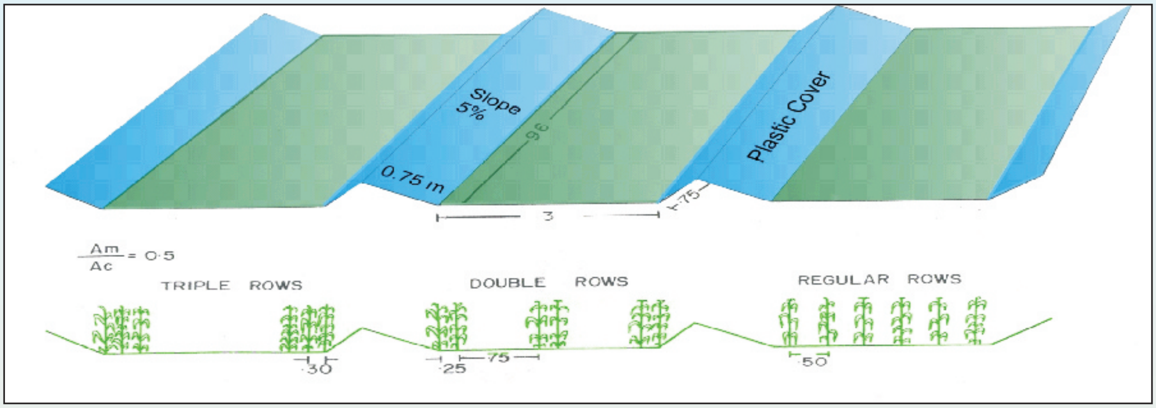


Fig. 4. *In-situ* water harvesting system.

Integration of regular row (RR) and double row (DR) plant geometries into water harvesting system on yield and water use efficiency of pearl millet best suited to runoff farming. In case of prolonged drought, 22% increase in yield with DR over RR was recorded (Singh, 1988). This increase was due to suppression of early plant growth, a mild crop canopy, micro-climate and conservation of water and nutrient by suppression of weed in DR system. Higher water storage in the 120 cm profile supported the pearl millet crop during ear emergence and grain development period thereby significantly increased the yield attributing characters. In the seasons with above normal, well-distributed rainfall, yield was similar for both RR and DR plant arrangements.

Water harvesting proved well particularly in low rainfall years. The yield of pearl millet was almost 3 times with water harvesting compared to conventional sowing (Table 8). In low rainfall situation *in-situ* water harvesting helped in making efficient use of limited rainfall and N-fertilizer in pearl millet. Application of 40 kg N ha^{-1} with *in-situ* water harvesting improved the pearl millet by 27% with 69 mm of additional runoff rainwater (Table 9).

Table 8. Water Use, yield and WUE of pearl millet by water harvesting

System	Good rainfall			Low rainfall		
	Water use (mm)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})	Water use (mm)	Yield (kg ha^{-1})	WUE (kg ha^{-1} mm^{-1})
Conventional	440	2320	5.3	143	400	2.9
In-situ water harvesting	630	2425	3.9	212	1240	5.9

Table 9. *In-situ* water harvesting makes efficient use of limited rainfall and N-fertilizer in pearl millet in low rainfall season (143 mm)

System	Added water (mm)	N- levels/yield of pearl millet (kg ha^{-1})	
		0	40
Rainfed	0	210	400
In-situ water harvesting	69	660	840

Micro catchment technique: Micro-catchment is one of the major forms of direct water conservation systems. Micro-catchment systems are relatively effective for use in growing trees and shrubs. In micro-catchment based cropping, rainwater is concentrated in a small portion of the cultivated area. The tree crops are deep rooted and can utilize the moisture stored in the sub-stratum and hence form a better option for micro-catchment based farming in sandy soil situations (Sharma *et al.,* 1986).

Arid horticultural plants like pomegranate, ber and several others can be successfully grown with appropriate micro-catchments in the water scarce regions. In micro-catchment systems, the donor to collector area ratios may range from 1: 1 to 20: 1. The various sizes of micro-catchments have been used for different purposes. The sizes may be up to 5 ha for annual crops, 31 -144 m^2 for *jujube* orchards in India (Yadav *et al.,* 1980), 0.35 ha for fuel wood plantation in Israel (Zohar *et al.,* 1988), 144-289 m^2 for fig, olive, pistachio plantation in Syria (Ibrahim, 1994). A number of catchment cropped area ratios and degree of slopes have been tried at CAZRI, Jodhpur. For *ber,* circular catchments of 1.5 m diameter and 5% inward slope with 54 m^2 of catchment has been found appropriate for conservation and proper utilization of rainwater (Sharma *et al.,* 1986). The circular micro-catchment and trenching techniques were compared for soil profile moisture storage in the arid region (Fig. 5). The study revealed that the 20% increase in soil moisture was observed due to circular catchment or trenching that with any soil treatment (Ojasvi *et al.,* 1999). For further improvement in water use efficiency, these circular micro-catchments can be covered with plastic sheet (LDPE).

Ex-situ Rainwater Conservation: Water Stored in Reservoir or Pond for Recycling

Ex-situ rainwater harvesting is a promising technology for enhancing the availability of water in arid areas. Ex-situ water harvesting involves collecting runoff originating from rainfall over a surface away from the field and storing it in surface storage systems for later use in the field. This type of rainwater harvesting provides supplemental or protective irrigation during dry periods of the cropping season.

Fig. 5. Circular catchment for water harvesting in ber.

PRESSURISED IRRIGATION

Irrigation is a major problem in the arid regions which are characterized as having low rainfall, highly permeable soils and poor quality of irrigation water. The conventional surface or aerial (sprinkler) irrigation system can solve these problems only partially. The most befitting technique for efficient utilization of costly irrigation water in these areas is the 'Drip' method of irrigation. "Drip irrigation" is a method of watering plants at a rate equivalent to (and not more than) its consumptive use so that the plants would not experience any moisture stress throughout their life cycle. In this method of irrigation water is conveyed from the source (i.e., tube well, dug-well or pond) through a network of pipe-lines (known as drip system) and finally released near the plant base. The primary objective of this type of irrigation is to provide optimum quantity of water to the crop for the maximum yield and simultaneously saving of valuable water from wastage; thereby increasing the water use efficiently.

Though flood method of irrigation has been followed predominantly all over the world for cultivating crops, but it is no longer desirable for countries like India mainly due to limited availability of water resources and growing demand for water for irrigation and other purposes. Therefore, for achieving sustainable agricultural development it is essential to increase the existing water use efficiency. Further, in view of the limited water resources, water is to be efficiently and economically used in arid and semi-arid conditions, for which pressurized irrigation systems can be one of the viable options.

The pressurized irrigation system has the capability of applying desired quantity of water both accurately and uniformly. Drip and sprinkler are the two examples of pressurized irrigation and both are able to save water as water is applied under pressure through a network of closed pipes, sprinkler nozzles and emitters. The energy required is imparted to the water by a pumping unit, which in turn receives energy from either an electric motor or internal combustion engine.

Advantages of Pressurized Irrigation

They provide a high degree of water application uniformity, often the highest of all irrigation systems in use.

They allow excellent control of the amount and timing of irrigation. Small and frequent irrigations can be applied to match the trees' water needs. Runoff is minimized because of the low application rates, and deep percolation losses can also be minimized if the correct amount of water is applied. The frequent irrigation provides an excellent soil water condition for optimal tree performance.

They can easily irrigate irregular terrain.

Weed growth is minimized since only desired portion is wetted.

Disadvantages of Pressurized Irrigation Systems

High initial cost of the systems

Excellent management is needed to maintain the system since clogging of the emitters by physical particles, organic materials, and/or chemical precipitates may occur.

The irrigation water must be pressurized, resulting in energy costs.

Cover crops cannot be grown throughout year due to the localized nature of the water applications.

DRIP IRRIGATION SYSTEM

Irrigation efficiencies under different methods of irrigation have been shown in Table 10. Research suggests that drip method of irrigation (DMI) is not only suitable for those areas that are presently under cultivation but it can also be operated efficiently in undulating terrain, rolling topography, hilly areas, barren land and areas which have shallow soils. Reduction in water consumption due to drip method of irrigation over the surface method of irrigation varies from 30 to 70 percent for different crops. According to data available from research stations, productivity gain due to drip method of irrigation is estimated to be in the range of 20 to 90% for different crops.

Table 10. Irrigation efficiency (%) under different methods of irrigation

Irrigation efficiencies	Methods of irrigation		
	Surface	Sprinkler	Drip
Conveyance efficiency	40-50 (canal)	100	100
	60-70 (well)		
Application efficiency	60-70	70-80	90
Surface water moisture evaporation	30-40	30-40	20-25
Overall efficiency	30-35	50-60	80-90

Source: Narayanamoorthy, 2009.

Components of Drip System

A pump or an overhead tank to generate pressure,

Main line to carry water from source (pump/tank) to the field,

Filter to remove solids,

Fertilizer tank to inject nutrients in the line,

Sub-mains to carry water to the sub-plots, and

Emitters to deliver water to the crop (Fig. 6).

Water Supply Manifold

Pipes: In drip systems pipes of schedule 40 and 80 are conventionally used. Similarly plastic tubing of different classes that can withstand different pressures are available. These may be used for mains and sub mains.

Filters: These are important components of the system as these remove suspended solids that may clog the emitters. Depending on water quality and emitter design, filters of different types, size and capacity may be selected. Mechanical filtrations include settling basins, sand separators or hydro cyclone filters based on centrifugal force or vortex motion, serene filters that are usually final filters in a series, sand or gravel filters having crushed granite or silica, and cartridge filters having paper fibre or fibre glass.

Fertilizer applicators: Fertilizers can be mixed in the irrigation water by (a) pressure differential, (b) the venturi and (c) metering pumps. In pressure differential system pressure difference is created between inlet and outlet through a valve resulting in mixing of fertilizer. In venturi rapid change in velocity reduces pressure that forces fertilizer in the line. In metering pumps a rotary, gear or piston is used to inject fertilizer in the line.

Emitters: These are the main components of the system through which water is discharged. Essentially emitters are of two types: (a) line source type and (b) point source type. In line source type the discharge points or orifices are closely spaced or there are continuous perforations or it has porous wall. It is suitable for closely spaced row crops. Point source types are either pressure compensating types (can withstand pressure variations, extent may depend on emitter type) or non-compensating types.

Similarly emitters may be in-line or on-line emitters. As the name indicates in-line emitters are embedded inside the tubing. Their advantages are: tubing is one piece thus can be easily stalled and rollup for reuse and since no joints are involved there is no leakage and friction losses. Disadvantages include, if need be their numbers cannot be changed. On-line emitters in contrast can be added as per requirement.

Crops, which have been grown with pressurized irrigation system, include the following:

Orchard crops: Grapes, citrus, apples, pomegranate, pears, delicious fruits (peaches, apricots, plums etc.), nuts (almonds, pistachios), bananas, dates, olives, mangoes, guavas etc.

Vegetables: Tomato, green pepper, cucumber, lettuce, green pea, cauliflower, okra etc.

Row and field crops: Cotton, sugarcane, corn, groundnut and onion.

Others: Berries, melons, alfalfa, flowers (carnations, gladioli and roses) and other ornamental plants

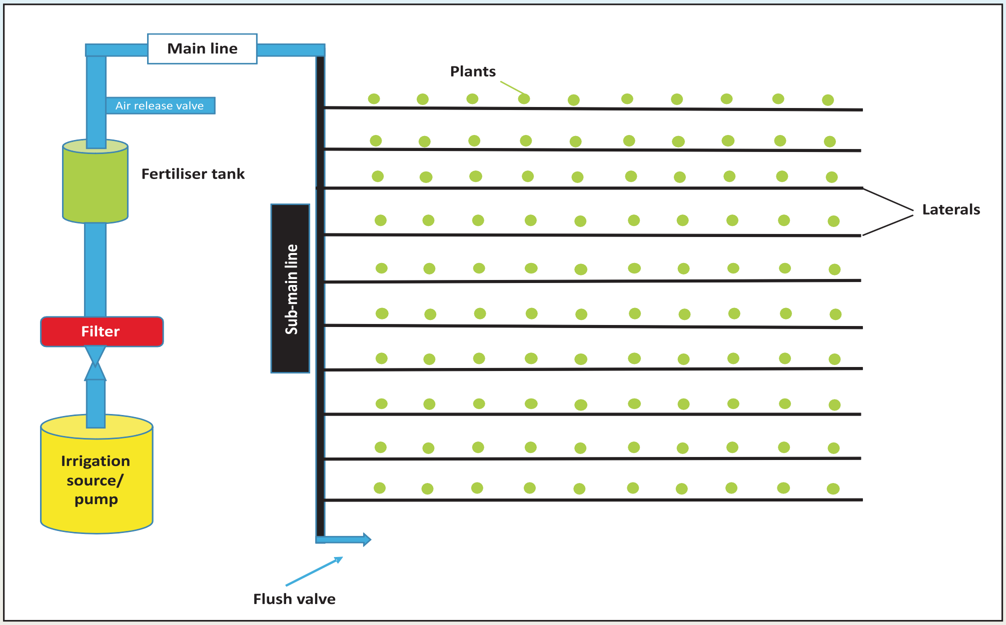


Fig. 6. Simple layout of drip irrigation system.

Planting Technique

Planting of seed or seedlings is done along the length of the lateral on one side or either side of it, irrespective of the position of the emitters on it. The emitters placed at a distance of 50 cm apart on a lateral line discharge the water at such rate that a continuous strip of about 40 cm width of soil remains wet throughout the length of the lateral. Different planting configurations (i) a single row (rectangular planting), (ii) double rows (square or equilateral planting) or (iii) triple row (hexagonal planting) were tried at CAZRI (Fig. 7). The major objective of such different types of planting is to reduce the number of laterals, thereby reducing the cost of the system without reducing the plant population in the field. The results of the study revealed that equilateral planting with the side of 25 cm to 35 cm of a triangle performed the best in almost all the crops tried (Table 11). Therefore, equilateral planting is advocated for vegetable crops like tomato, cabbage, cauliflower, turnip etc.

Paired row planting with single lateral of drip combined with mulch resulted 40-50% saving in water and higher production of tomatoes. Drip irrigation at ET 100 saved 35% water and produced 40% higher yield over conventional irrigation. Drip ET 50 though yielded at par with conventional irrigation but saved 50% water (Research Highlights, CAZRI, RRS, Pali, 1959-2009).

Table 11. Effect of planting configurations on crop yields

Plant arrangement	Yield (metric t ha^{-1})			
	Cabbage	Tomato	Turnip	Cauliflower
Rectangular	35.5	68.4	19.5	20.0
Square	33.2	73.1	20.3	23.8
Hexagonal	16.9	55.1	11.8	13.2
Equilateral	33.0	78.4	22.9	26.0

Source: Singh *et al.*, 1989.

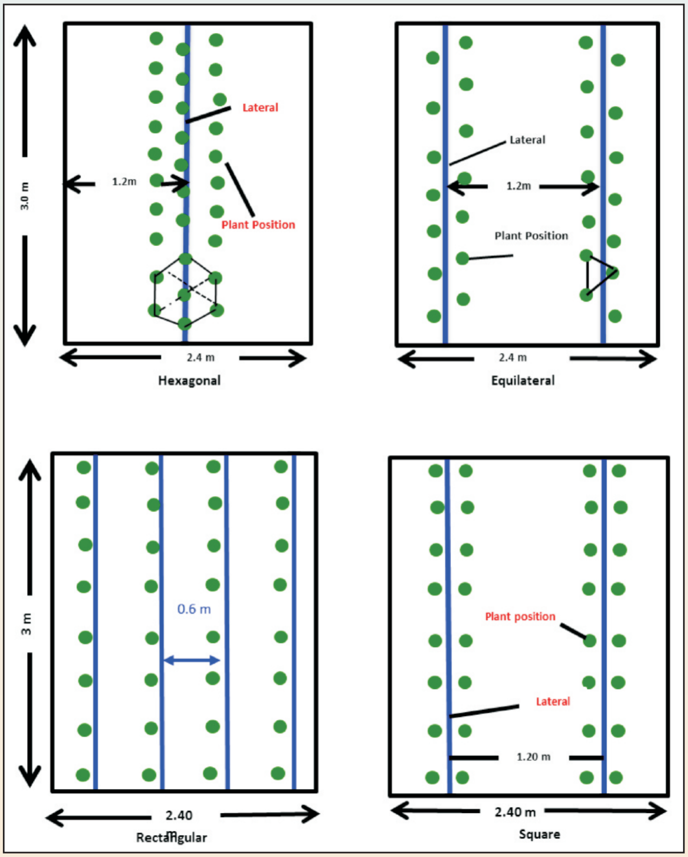


Fig. 7. Planting configurations under drip irrigation.

Irrigation Scheduling and Frequency

The main objective of the drip method of irrigation is to provide each plant with a continuous supply of soil moisture which is just sufficient to meet the evapo-transpiration demand. Thus it is desirable to irrigate the field daily at the end of the day break. The unique feature in drip method of irrigation is that since the water loss of the day is duly compensated every evening, the root soil always remaining nearly at the field capacity and consequently the crop never suffers from moisture stresses. This is the main reason for higher yield of crops as compared to other method of irrigations (Fig. 8).

Fig. 8. Drip field layout for ladyfinger at CAZRI.

The potential evapo-transpiration as obtained from USDA class A pan may be multiplied with crop factor (approximately 0.7) to get daily consumptive use of crop. For a layman this approximate quantity or irrigation requirement may be translated into time period (in minutes) for which the system may be kept opened in a usual sunny or cloudy day of the *rabi* season (Shankarnarayan *et al*., 1984). However, it has been observed by the scientists that by increasing the quantity of water in irrigation by 30 above the consumptive use through drip system the subsequent irrigation can be delayed by 2 days without much adverse effect.

Drip irrigation in cotton at 0.8 ETc gave 27.5% higher seed cotton yield compared to yield with furrow irrigation (1801 kg ha^{-1}) at CAZRI RRS Pali. Decrease in seed yield of cotton was 6.3% at 0.8 ETc and 25.5% at 0.6 ETc irrigation levels compared to full irrigation (1.0 ETc) (CAZRI Annual Report 2010-11).

Drip Irrigation for Horticultural Crops

Drip method of irrigation is more economical for orchard crops than that for the vegetables. In orchards of ber, lemon, date-palm, pomegranate, etc. the plants as well as rows are kept almost 5 to 8 metre apart which necessitates where the laterals are spaced nearly 1 m to 1.5 m apart. The drippers for fruit trees are different from that of vegetable plants. Moreover, less number of drippers are used in each of the lateral lines. For example, in a lateral line of 30 m length laid out for tomato crops nearly 60 drippers are fixed on each lateral while for the same length of lateral to be used in ber orchard of grown up trees only 25 to 30 drippers will be necessary depending upon the quantity of water required. On the other hand it has been found that in arid areas these fruit trees when irrigated produce almost two times the fruit as compared to that in unirrigated conditions.

Use of Drip Irrigation for Saline Water Irrigation

In desert, over 60% of the total area has the problem of groundwater salinity. Conventional irrigation with saline water caused considerable reduction in yield and deteriorated the soil health. Drip method of irrigation has its adaptability to saline water irrigation. Since the frequency of irrigation in this method is quite high (i.e. every day) the plant base always remains wet which keeps the salt concentration in the plant root zone below the critical level that may be hazardous for the plant growth. The maximum salt concentration occurs around the periphery of the wet zone. Therefore, studies were conducted using drip irrigation to evaluate the utility of drip system in applying saline water. Study revealed that yield of potatoes irrigated by drip irrigation with water with a conductivity of 3 dS m^{-1} was 31% higher than that of furrow irrigation using good quality water (Table 12). In case of tomato, the yield obtaining using water of conductivity of 10 dS m^{-1} was nearly 14% less than that of sweet water. Daily drip irrigation provided gainful use of poor quality water in potato and tomato maintaining higher water content in the rooting volume and forcing the salts to the sides and below the root zone. Hence, drip system has shown the potential to use substandard water in our desert (Singh *et al.*, 1978).

Drip irrigation in pomegranate with saline water (EC 9.5 dS m^{-1}) resulted in better growth, canopy and fruit yield (2.6 kg per plant) of pomegranate over ring basin irrigation system (Research Highlights, CAZRI, RRS, Pali, 1959-2009).

Table 12. Gainful use of saline water in potato and tomato under drip irrigation system

System	Salinity (dS m^{-1})	Potato (t ha^{-1})	Tomato (t ha^{-1})
Drip	3	26	50
Drip	10	-	44
Conventional	0.08	20	50

Source: Shankarnarayan and Singh, 1985.

Fertigation - Combining Fertilization with Drip Irrigation

During the irrigation process the plant roots uptake nutrients (nitrogen, potassium) at a rate of up to 4-6 kg ha^{-1} day^{-1}. As in drip irrigation the volume of the root system is relatively small and the amount of nutrients available in the soil is quite limited. Furthermore, the water flowing through the zone of the root system washes away dissolved salts, including nutrients. Therefore, it is essential to resupply nutrients to the root system, particularly nitrogen, which is highly soluble in water and is rapidly depleted from the root zone. Although potassium and phosphorus are less soluble and will be washed downward at a slower rate, there is a need to replenish them, especially in sandy soil.

Several methods have been developed to provide the plants during the growing season with required nutrients as often as necessary via the irrigation system. In fertigation the water discharged by the drippers actually constitutes nutrient solution. The composition of the nutrients in the solution and the concentration of each component can be adjusted in accordance with the specific needs of each crop at various times during the season. Each of the fertilizers used in fertigation needs to be highly soluble in water and free of undissolved residues. In the case of water rich in calcium (hard water) sedimentation may occur when phosphates are introduced to the water. To overcome this problem it is recommended to use either phosphoric acid or a compounded acidic fertilizer. Several devices are available for delivery of fertilizers via the irrigation system including a metal container for delivering fertilizers, pumps operating a venturi tube, and a wide range of pumps with different mechanisms and control devices.

Investigations were carried out at CAZRI, Jodhpur to economize and improve nutrients' efficiency with drip irrigation for tomato crop. Higher moisture content maintained with drip irrigation make the nutrients in available form to the crop (Singh *et* *al.*, 1989; Singh *et al.*, 1999). The fertilizer (one fourth of total fertilizer) applied on planted area basis with drip provided higher yield than broadcast application in check basin (Table 13). This shows a saving of 75% fertilizer with drip irrigation over conventional irrigation.

Table 13. Effect of fertility level on tomato crop

Method of fertilization	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potash (kg ha^{-1})	Tomato yield (t ha^{-1})
Surface (B)	224	88	168	50
Drip	56	22	42	60

Drip irrigation system was demonstrated in a farmer's field for tomato cultivation by CAZRI for six years in 0.4 ha land for ascertaining the advantages derived from drip irrigation system. In flood irrigation system only 0.24 ha of land was irrigated as compared to 0.4 ha of land under the drip irrigation system with the same quantity of water. As such an increase of 66.6% more land was brought under irrigation. The tomato yield was obtained to the tune of 60 q ha^{-1} (Chauhan *et al.*, 1988).

The drip irrigation is neither affected by winds nor by saline water as it applies water directly in the rooting volume of crops. Studies conducted at CAZRI Jodhpur revealed that drip saves 30-50% water and provide 2-3 times higher yield than conventional irrigation (Singh and Saxena, 2001). Experiment conducted at CAZRI, Jodhpur with drip irrigation system and furrow irrigation system of surface irrigation method showed significant amount of water saving (50%) for potato crop without losing much yield (Table14). Adoption of drip irrigation in chillies resulted in 71% increase in yields over surface furrow irrigation (Singh *et al.*, 1999) at CAZRI Jodhpur.

Table 14. Saving of water in potato crop under drip irrigation system

Irrigation method	Water use (cm)	Yield (t ha^{-1})
Drip – ET 50	16	18
Furrow – ET 100	35	19

Under an experiment conducted at CAZRI, Jodhpur for assessment of yield of muskmelon, ladyfinger and tomato, drip system gave higher yields of 17.7, 37.8 and 22.6% compared to the yield under check-basin irrigation (Table 15).

Higher water use efficiency and water productivity under drip irrigation over conventional method of irrigation (check basin) of crop sequences is presented in

Table 16. Lady finger-tomato-muskmelon crop sequence for a year with drip irrigation gave maximum water productivity (Figs. 9-12).

Fig. 9. Ladyfinger crop under drip irrigation.

Fig. 10. Tomato crop with drip irrigation.

Fig. 11. Muskmelon under drip irrigation.

Table 15. Yield of crops in cropping system (t ha^{-1})

Manure (2.5 t ha^{-1})	Ladyfinger		Tomato		Muskmelon	
	Drip	Check basin	Drip	Check basin	Drip	Check basin
Vermi-compost + Inorganic Fert.	5.8	3.9	55.0	44.0	45.3	36.6
FYM + Inorganic Fert.	5.4	3.6	49.6	40.3	43.4	35.0
N_{80}	6.4	4.4	57.4	48.5	46.9	39.4
N_{60}	4.6	3.7	51.1	41.6	40.3	36.1
N_{40}	3.2	2.9	46.2	37.1	36.4	33.2
Mean	5.1	3.7	51.9	42.3	42.5	36.1

Source: Annual Report 2010-11, CAZRI, Jodhpur.

Application of micronutrients through drip irrigation in groundnut increased pod and haulm yields, shelling out-turn, seed mass and sound mature seeds (SMS) and nutrient use efficiency over their soil and foliar applications. The drip application of Fe, Zn and B increased pod yield by 31-36, 21-23 and 15-21%, respectively over control (Singh *et al.*, 2001). Further, it was recommended to apply micronutrients through drip irrigation for better nutrient utilization and high groundnut yield in semi-arid region.

Table 16. Water use efficiency and water productivity of different sequences

System	Water use efficiency (kg ha^{-1} mm^{-1})				Water productivity (kg m^{-3})
	Rainy	Winter	Summer	Mean	
Drip Irrigation					
Lady finger-tomato-lady finger	20.1	10.7	14.1	14.9	1.49
Tomato-gladiolus-lady finger	10.5	–	14.1	–	–
Lady finger-tomato- muskmelon	20.1	10.7	21.2	17.3	1.73
Lady finger-gladiolus-muskmelon	20.1	–	21.2	–	–
Check-basin					
Lady finger-tomato-lady finger	6.5	8.0	6.1	6.9	0.69
Tomato-gladiolus-lady finger	7.3	–	6.1	–	–
Lady finger-tomato- muskmelon	6.5	8.0	15.5	10.0	1.00
Lady finger-gladiolus-muskmelon	6.5	–	15.5	–	–

Fig. 12. Cut flower (Gladiolus) under drip.

Maintenance of Drip Irrigation System

Drip irrigation systems requires regular maintenance. Maintenance plan and checklist has been presented in Table 17 and 18.

Table 17. Components of maintenance plan for drip irrigation systems

Component	Description
Filtration	Remove solid particles from the water. (Sand filters, disc filters, screen filters or centrifugal sand separators, 200 mesh or equivalent for screen and disk filters)
Chlorination	Hypochlorous acid (HOCl) reacts with microorganisms in water and precipitate ions in solution. Residual Cl (1 ppm) concentration at the end of drip line indicates adequate reaction
Acidification	Reduce pH to around 6.5 and increase efficiency of chlorination and other precipitates. Acid injections are used for calcium deposits
Flushing	Allow solid particles and precipitates to leave the drip line by ways other than the emitters (end of drip line)

Table 18. Maintenance checklist for drip system during growing season

What to check	Frequency	What to look for	Possible causes
Pump flow rate and pressures for each zone	Weekly	High flow and /or low pressure Low flow and/or high pressure	Leaks in pipelines Opened ends of laterals or flush valves, Tube clogging, Pump malfunction, Well problems
Pressure difference across filter	Every irrigation	Exceeds or is close to maximum allowable	Filter becoming clogged Obstruction in filter
Operating pressures at ends of laterals	Monthly	Pressure greater/ lower than expected	Possible clogging; High system pressure; Broken lateral; Leaks in lateral
Water at lateral ends and flush valves	Bi-weekly	Particles in water other debris	Broken pipeline; Filter problem; Fertilizer precipitation; Algae or bacterial growth

Drip method of irrigation is undoubtedly a superior water management practice as compared to other methods of irrigation for arid regions. The only limitation is that it requires high initial investment at the outset. About Rs. 50,000 is to be spent for vegetable crops and Rs. 25,000 for orchard crops at the beginning for layout of the system in one hectare of area. The recovery of the cost depends upon the type of crops selected and the period (*rabi* or *kharif* or both) the system is used for different crops. It has been found experimentally that the cost can be realized by the farmers within 2 or at least 2 years if multiple cropping is done by drip system.

SPRINKLER IRRIGATION SYSTEM

In sprinkler irrigation, water is sprayed into the air and allowed to fall on the ground surface similar to natural rainfall. The flow of water under pressure passes through small orifices or nozzles resulting into spray. The pressure is usually obtained by pumping. It is then sprayed into the air through sprinklers so that it breaks up into tiny water drops which fall on the ground. Careful selection of nozzle sizes, operating pressures and sprinkler spacing helps in applying water uniformly at a rate to suit the infiltration rate of the soil, thereby obtaining efficient irrigation. An understanding of the advantages and limitations inherent in sprinkler irrigation will enable its optimum use.

Advantages

- Suits to complete range of topographies and field dimensions
- Wide range of irrigation intensity can be changed with the infiltration capacity of the soil
- Easy to operate. Operators may be trained quickly. Even unskilled personnel can operate the irrigation systems reasonably well
- High irrigation efficiency due to uniform distribution of water
- Accurate and easy measurement of water applied
- Application of fertilizers through the irrigation system
- Mobility, enabling the exploitation of one irrigation unit for the irrigation of many plots
- Can maintain micro-climate protection against frost

Limitations

- Pressure is required for operation which means an investment in energy
- Difficulties of irrigation during wind conditions, poor water distribution, and drift outside area
- Loss of water due to evaporation from the area during irrigation
- Loss of water from the marginal areas especially in small and irregular plots
- Sprinkling water may aggravate incidence of disease and washing off of spray materials

The use of poor quality water may cause leaf burn and leaf fall

Sprinkling at high intensities and high application rates that are not adjusted to the soil will cause run-off

Adaptability of Sprinkler Irrigation

Sprinkler irrigation can be employed for most of the crops and on most soils. It is, however, not usually suitable in heavy clay soils where the infiltration rates are less than about 4 mm per hour. The method is particularly suited to sandy soils that have a high infiltration rate. Too shallow soils to be leveled properly for surface irrigation methods; can be irrigated safely by sprinklers. It is especially suitable for steep slopes or irregular topography (dune area).

Land leveling is not essential for irrigation with sprinklers. Some smoothing or grading is advisable, if surface drainage is a problem or to provide a more uniform surface for seeding, tillage and harvesting. Land too steep for efficient irrigation by other methods can be irrigated safely. Small streams of irrigation water can be used efficiently, and well-designed sprinklers distribute water better than in other methods. Surface runoff of irrigation water can be eliminated. The amount of water can be controlled to meet crop needs, and light application can be made efficiently on seedlings and young plants.

Soluble fertilizers, herbicides and fungicides can be applied in the irrigation water economically and with little extra equipment. Penetration of fertilizers into the soil can be controlled by applying the fertilizer at selected times during the application of water. Sprinkler irrigation can be used to protect crops against frost and against high temperatures that reduce the quantity and quality of harvest. Labour costs are usually less than for surface methods on soils having a high infiltration rate and on steep and rolling land. More land is available for cropping. Field supply channels and bunds or ridges are not required. The irrigation method does not interfere with the movement of farm machinery.

Classification of Sprinklers

Sprinklers may be classified in accordance with levels of optimal operating pressures – low, medium or high.

Low pressure (up to 20 m): Suitable for whirling sprinklers, turbo-hammer and propeller sprinklers

Medium pressure (up to 50 m): Suitable for hammer and propeller sprinklers

High pressure (above 50 m): Giant ("cannon") sprinklers or large hammer sprinklers

Levels of pressure i.e. low, optimum and high have been depicted in Figs. 13-15.

Discharge range may be classified similarly to pressure range-low, medium and high

Low discharge: Mainly sprinklers used in orchards and gardens discharge is tens of thousands of liters

Medium discharge: Field crops-several m^3 hr^{-1}

High discharge: Giant sprinklers-tens of m^3 hr^{-1}

Principles of Operation

Most sprinklers used in field crops are activated by the hammer mechanism. Other types include:

Whirling sprinkler: Water jet emitted from the end of the arm results in a reverse rotary movement at relatively high speed. The whirling sprinkler may have one, two or three nozzles and operates under low pressure. Coverage area is small and mainly used in orchards and gardens.

Turbo-hammer: Water jet operates a wheel which activates the hammer and causes the sprinkler to turn. The turbo-hammer is manufactured from plastic materials. It is used for irrigation of orchards and gardens and has low discharge.

Propeller: Water jet strikes propeller which rotates at high speed around its shaft and causes a circular motion of the sprinkler. The propeller breaks the jet into very fine drops and consequently irrigation intensity is low. It is made of plastic material and used in solid sets for field crops.

Mini-sprinkler: Water jet strikes a bearing possessing one or two channels resulting the mini-sprinkler to rotate quickly and distribute the water. It is manufactured from plastic materials and is used in solid sets in orchards and gardens. It is small in size and gives low discharge.

Usage

Sprinklers with low angle jets: Under canopy sprinklers

Giant (cannon) sprinklers: Irrigation of cereals and fodder crops, wide spacing covering large areas

Part circle sprinklers: For part circle irrigation of marginal areas to prevent wastage of water and wetting of roads

Pop-up sprinklers: For lawns and gardens. Inserted underground with cover, pop-up when valve is opened and drop when valve is closed

Regulated sprinklers: These may be either discharge or pressure regulated

Selection of Sprinklers

Selection of sprinkler depends on crop, soil and quality of irrigation water, irrigation schedules, water supply conditions (pressure, discharge, availability) and labor availability etc. Apart from this, sprinkler characteristics must be taken into account, viz., quality of water application, pressure and discharge range, and sensitivity to wind. The final decision of choosing the right sprinkler generally is guided by the limitations – low pressure, wind conditions, infiltration rate of soil and availability of water.

Irrigation Planning

An irrigation system is planned so that the correct amount of water will be applied efficiently at the right time. Some of the planning considerations are crop requirements (irrigation schedules), soil type (available water capacity, infiltration rate), precipitation, wind, evaporation, water quality (physical and chemical), water supply conditions (discharge, pressure, time), topography and shape of field, labor and economic considerations. The irrigation system will be selected after a complete evaluation considering all factors. Specific limitations will affect decisions.

The basis of good planning depends upon the provision of exact and reliable data by the farmer to the planner. The data will include: a topographical scale map with details of borders, paths, direction of tillage and rows, existing network, ditches, electricity lines and the like, crop irrigation schedules, including special requirements (day or night irrigation, above or below canopy), water supply conditions and water source, soil data (soil analyses), agro-technical considerations, and any other relevant data. The planning of a specific field (i.e., the specific area which represents a unit of cultivation, treatment and irrigation) will be carried out in stages.

After collecting and analyzing the data, the planner will select the sprinkler (type and nozzle size), determine layout and duration of cycle and thus determine required discharge. Pipe diameters will be chosen and calculated in accordance with the basic principles allowing for maximum differences of discharge of up to 10% of the average discharge of sprinklers operated simultaneously. The pressure required at the head of the field will also be calculated. At this stage the considerations will be hourly discharge, pressure and other limitations of the system, water conveyance and source of water, organization of labor.

The uniformity of application achieved under field conditions depends on (i) the type of sprinkler pattern, (ii) the spacing of sprinklers, and (iii) the effect of such factors as wind, variation in rotation of sprinklers, tilting of sprinkler risers etc.

The sprinkler pattern is the shape of the volume of water falling on the area wetted and can be represented by a vertical section through the sprinkler location or by contours showing the depth of water applied. Under ideal conditions this pattern is symmetrical around the sprinkler, but under field conditions it is seldom so. Wind distorts and offsets the pattern. Lack of uniformity of rotation and tilting of sprinkler risers also distorts the pattern. Pressures below that for which the sprinkler is designed produce low applications near the sprinklers and excessive applications in a ring around the sprinklers.

The triangular shaped pattern with maximum application at the sprinkler and gradual reduction in application to the edges of the area covered produce the most uniform application when sprinklers are spaced not more than about 55% of the diameter wetted by the sprinkler. For rectangular sprinkler arrangements with closer spacing on the laterals the spacing between laterals can be increased slightly. For a square arrangements of sprinklers, it is theoretically possible to obtain high uniformity coefficients with the spacing between laterals upto about 70% of the diameter covered by the sprinkler; for an equilateral triangle arrangement of sprinklers, up to 75% of the diameter. The ideal pattern for wide spacing have a uniform application to about 50% of the radius covered then the application reduces uniformly. Such patterns are very sensitive to correct spacing, and the uniformity obtainable is lower for spacing both less and greater than the optimum because of excessive or insufficient overlap. For triangular patterns, the uniformity remains high for all spacing upto about 55% of the diameter covered. For securing a greater seasonal uniformity of application the laterals may be alternated, i.e. for successive applications to place the lateral midway between the positions occupied during the previous irrigation.

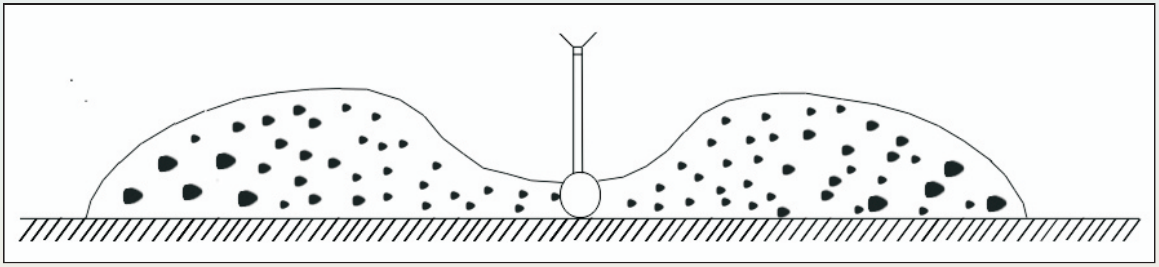


Fig. 13. Sprinkler system operating at too low pressure.

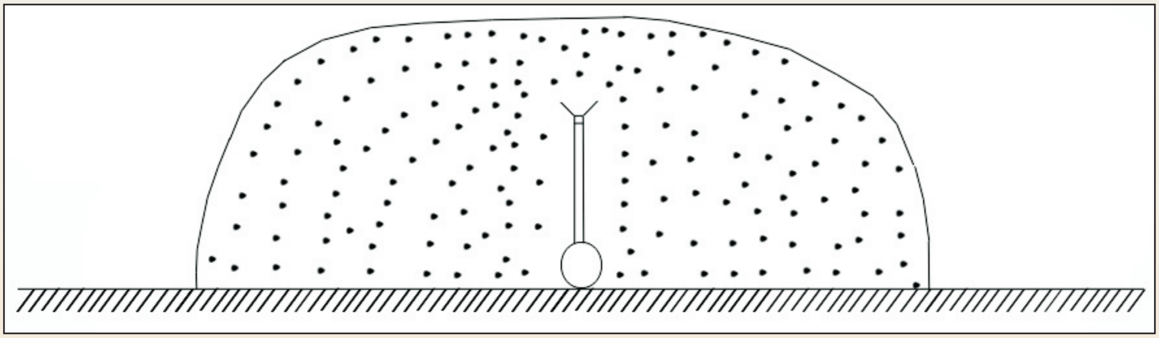


Fig. 14. Sprinkler system operating at too high pressure.

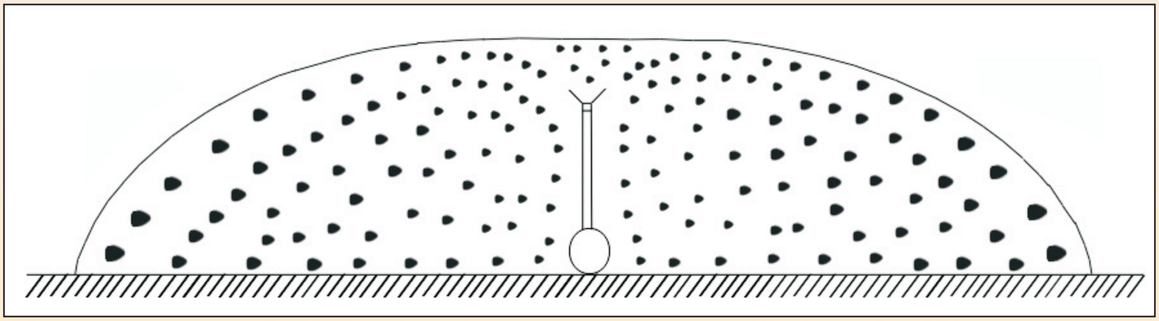


Fig. 15. Sprinkler system operating at optimum pressure.

Spacing is determined according to uniformity of water application and type of equipment (viz. available lengths of aluminum or plastic pipes). The recommendations define the type of sprinkler, nozzles, wind speeds, pressure range and spacing. Fig 16a and b depicts the water uniformity under overlap condition of sprinklers. If overlap is less than 50% of wetted diameter it will lead to non uniform application of water resulting in poor irrigation efficency.

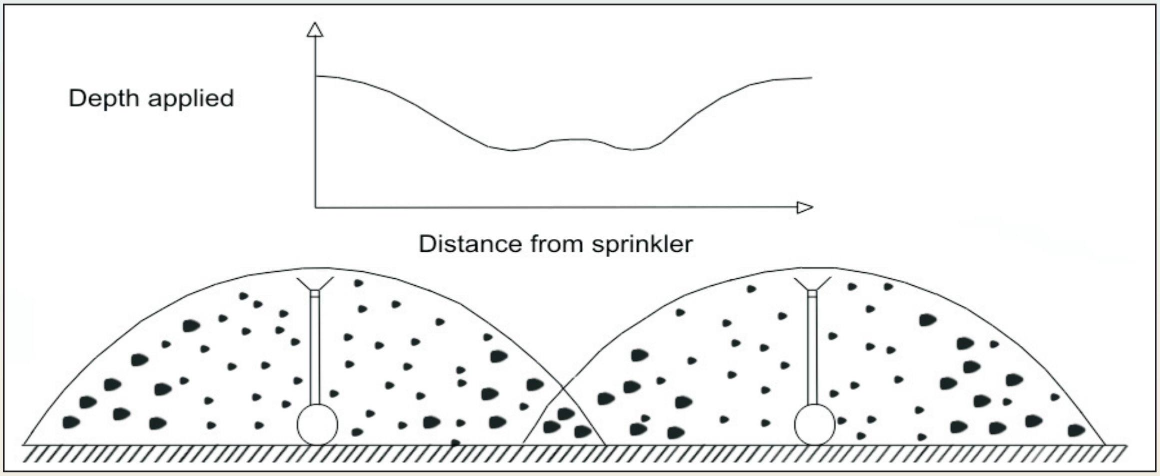


Fig 16a. Non-uniform application: Overlap << 50% of sprinkler wetted diameter.

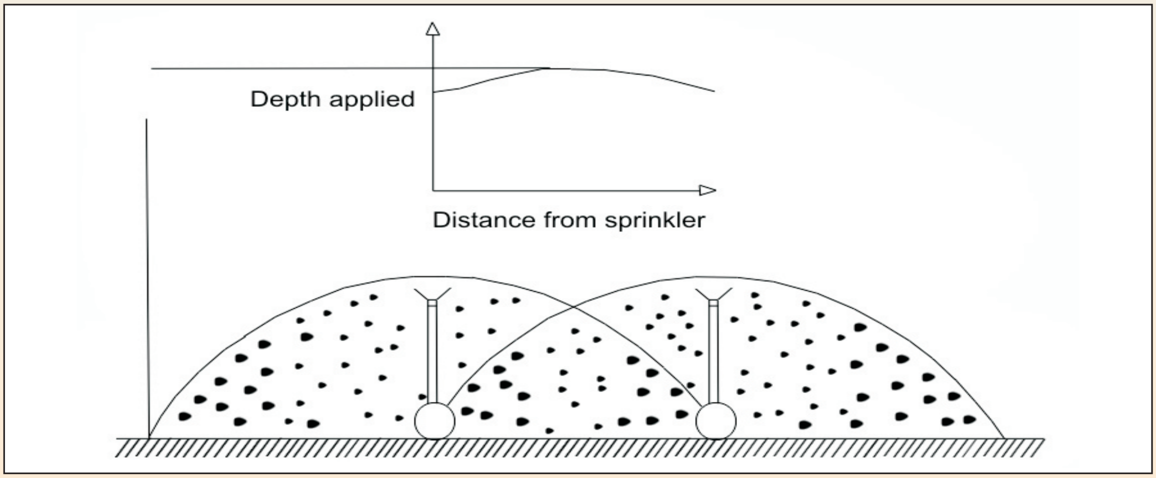


Fig 16b. Uniform application: Overlap 50% of sprinkler wetted diameter.

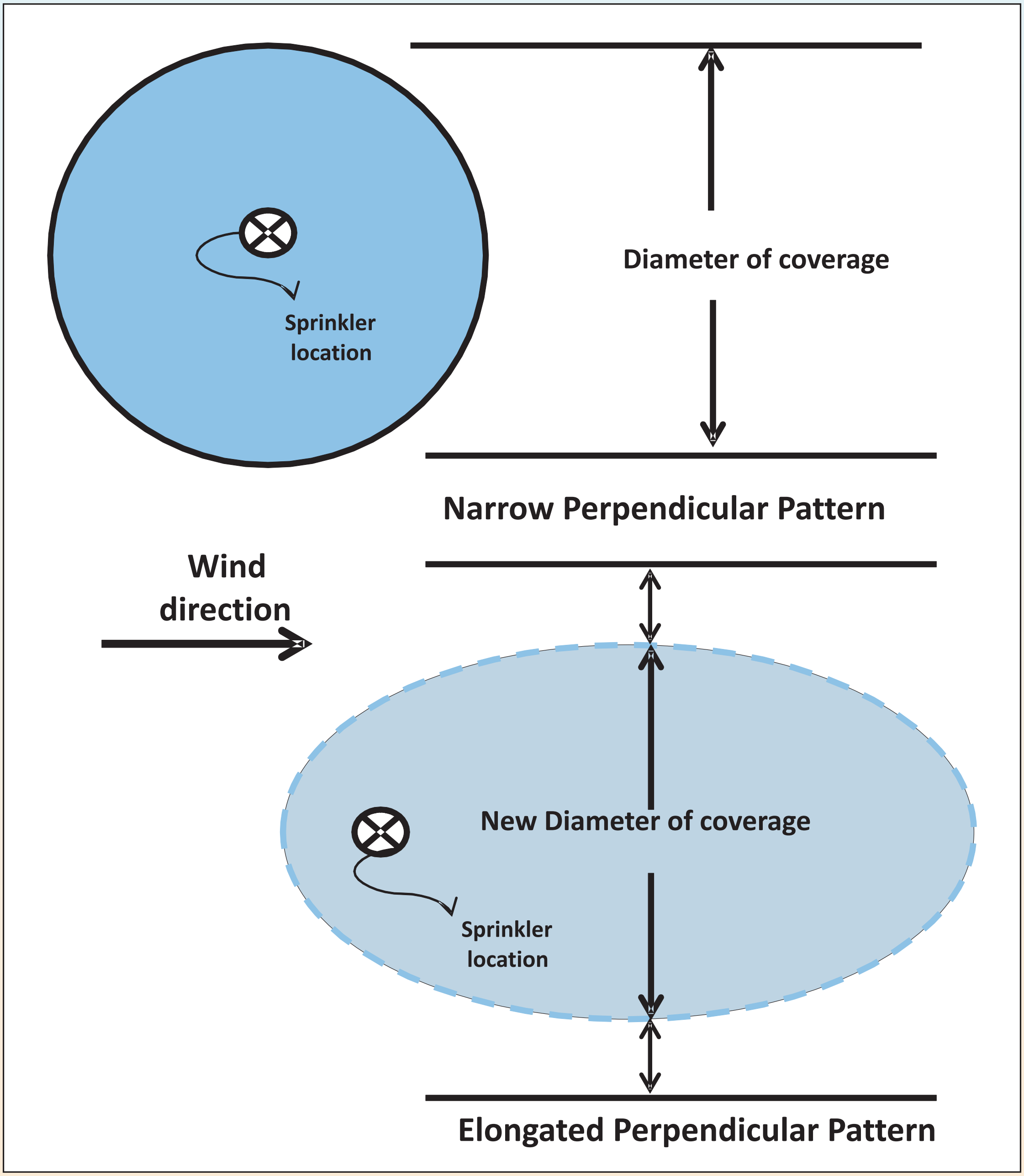


Fig. 17a. Distortion in application pattern due to windy conditions.

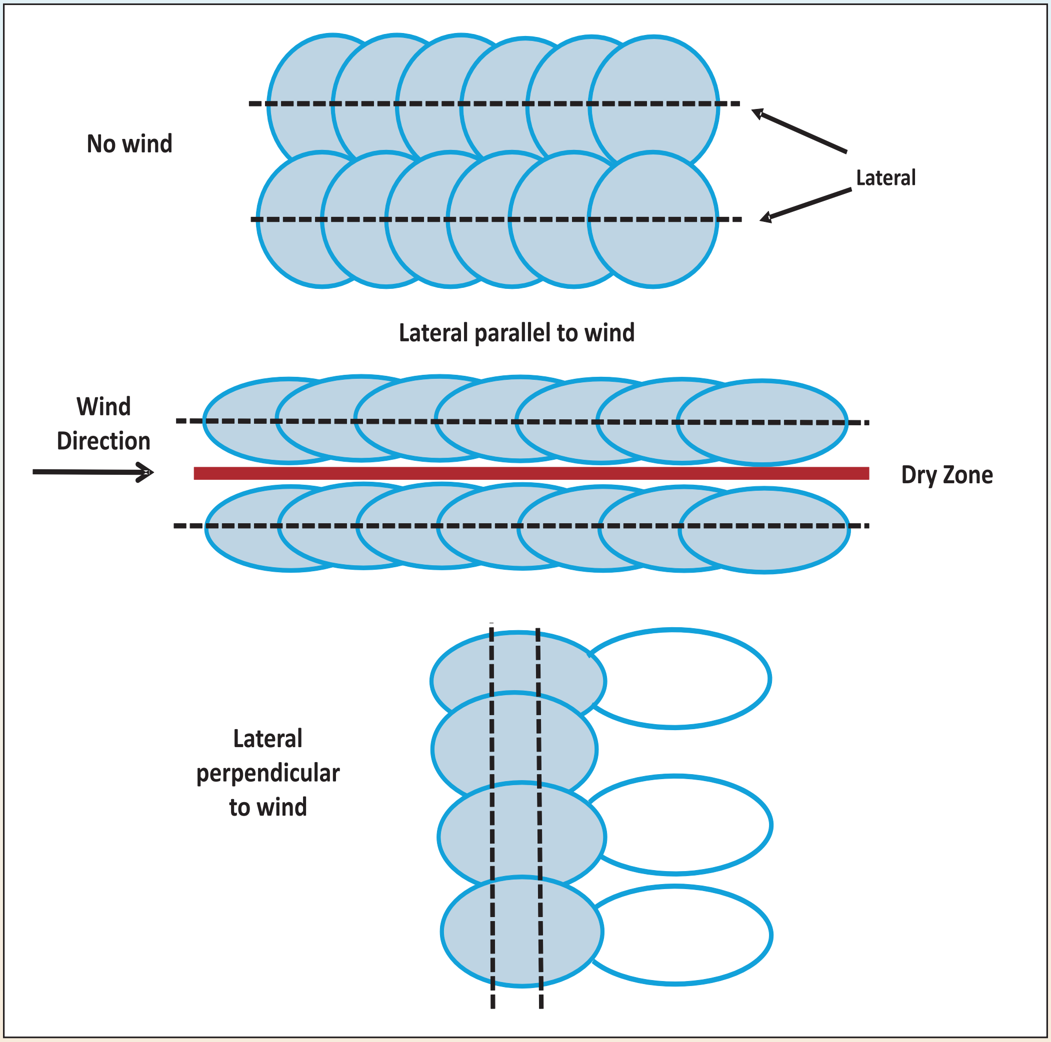


Fig. 17b. Distortion in application pattern due to windy conditions.

The application rate affects the water distribution under varying wind conditions. The higher the application rate, the greater the resistance to wind. Irrigation in windy conditions will lead to dry zone between two laterals (Fig. 17a & b). To reduce the wind effects, it is desirable to irrigate under zero wind conditions. When it is not feasible, decrease the spacing and increase the nozzle sizes according to the infiltration capacity of the soil. Maximum spacing of sprinklers under different wind conditions is given in Table 19.

Table 19. Maximum spacing of sprinklers under wind

Average wind speed, km h^{-1}	Spacing
No wind	65% of the diameter of water spread area of a sprinkler head
0-6.5	60% of the diameter of water spread area of a sprinkler head
6.5-13.0	50% of the diameter of water spread area of a sprinkler head
Above 13.0	30% of the diameter of water spread area of a sprinkler head

Fertigation (Fertilizer + Irrigation) Devices

Fertilizers may be combined with sprinkler systems. The fertilizer will be introduced at the head of the plot or at the head of a large block. Precautions must be taken to ensure that irrigation water containing fertilizer is not used as a source of drinking. There are a number of different methods and fertigation devices each operating under different principles:

Fertilizer tank with bypass flow

Venturi

Injection pump operated by a combustion engine, electricity or water

Fertigation may be continuous or part of the irrigation. The allocation of the fertilizer may be quantitative or proportional.

The effect of drip, sprinkler and furrow irrigation on long gourd, ridge gourd, round gourd and watermelon was studied at CAZRI, Jodhpur. Almost same amount of water was applied through conduit pipes in conventional, sprinkler and drip systems. The water applied was 69 cm in drip and 84 cm in sprinkler and furrow irrigation. The benefits of drip irrigation were not the same for all the crops. Increase in yield from drip irrigation over sprinkler and furrow irrigation was 44-47% in long gourd, 21-37% in round gourd, 9-22 % in watermelon and practically nil in ridge gourd (Table 20). Further, water use efficiencies were 8.1, 6.5 and 11.0 kg ha^{-1} m^{3} in long gourd, round gourd and watermelon, respectively. Sprinkler system also showed superiority over conventional method (furrow) in terms of yield.

Table 20. Yield (t ha^{-1}) of various crops under different methods of irrigation

Irrigation method	Long gourd	Ridge gourd	Watermelon	Round gourd
Drip	56	12	82	41
Sprinkler	39	10	75	34
Furrow	38	11	67	30

Under a demonstration of sprinkler irrigation system at farmer's field, yield of pearl millet increased by 64% and of wheat by 153% as compared to flood irrigation. Similarly the yield of mustard increased from 770 kg ha^{-1} to 1657 kg ha^{-1} compared to flood irrigation. It also saved 31 man days per hectare for preparation of plots which is to be done under the flood system of irrigation (Chauhan *et al.*, 1988).

STEPWISE DETERMINATION OF IRRIGATION REGIMES

1. Available water depth (mm/Zr) in the main root zone (AWDZr)

$$AWDZr \quad (Fc \quad Pw) \times \frac{As}{Dw} Zr \times 10$$

Fc-Pw = Field capacity and PWP expressed in moisture % by weight
As = Apparent specific gravity (g cm^{-3})
Dw = Water density (g cm^{-3})
Zr = Main root zone of the crop (m)

2. Available water volume (m^3/ha/Zr) in the main root zone (AWVZr)

AWVZR = AWDZr x 10

3. Net water depth application (NWDA, mm/Zr)

$$NWDA \quad \frac{AWDZr \times PWD(\%)}{100}$$

AWZr = Available water depth in the effective root zone (mm/Zr)
PWD = Permitted water deficit (Consumed by the crop)

4. Percentage of wetted area (PWA)

Recommended values of PWA for different irrigation systems

Irrigation system	PWA (%)
Sprinkler	100
Micro-sprinkler	50-75
Drip	30-70

5. Irrigation interval (Irl, days)

$$Irl \quad \frac{NWDA \times PWD(\%)}{ETc \times 100}$$

NWDA = Net water depth application (mm)
PWA = Percentage water deficit (%)
ETc = Crop evapotranspiration (mm/day)

For designing ETc should be taken at peak moisture demand

Adjusted irrigation interval – Irl (adj.)

Irl (adj.) = Irl (entire number days, without decimal)

6. Irrigation cycle – IrC

IrC = Irl (adj.) – Sd (days)

Sd = Spare days (system failure, break)

7. Adjusted net water depth application (NWDA (adj.))

$$\text{NWDA(adj.)} \quad \frac{\text{Irl(adj.)} \times \text{ETc} \times 100}{\text{PWA(\%)}}$$

NWDA (adj.) = Adjusted net water depth application (mm)
Itl (adj.) = Adjusted irrigation interval (days)
ETc = Crop evapotranspiration (mm/day)
PWA = Percentage wetted area (%)

8. Adjusted percentage "permitted water deficit" (PWD (adj.))

$$\text{PWD(adj.)} \quad \frac{\text{NWDA(adj.)} \times 100}{\text{AWDZr}}$$

PWD (adj.) $\leq$ PWD

9. Irrigation efficiency (Ef, %)

$$\text{Ef} \quad \frac{\text{NWDA(mm)}}{\text{GWDA(mm)}} \times 100$$

10. Gross water depth application (GWDA, mm)

$$\text{GWDA} \quad \frac{\text{NWDA(adj.)} \times 100}{\text{Ef}}$$

11. Gross water volume application (GWVA, $m^3\ ha^{-1}$)

$$GWDA \quad \frac{GWDA \times PWA}{10}$$

GWDA = Gross water depth application ($mm = 1/m^2$)
PWA = Percentage wetted area (%)

12. Effective precipitation rate of irrigation system (Epr, $mm\ h^{-1}$)

$$Epr \quad \frac{qe \times 100}{Se \times Sl \times PWA}$$

qe = Emitter discharge (l/h)
Se = Emitter spacing on the line (m)
Sl = Lateral spacing (m)
PWA = Percentage wetted area (%)

In order to prevent runoff, the Epr must be lower than the basic infiltration rate (Ib) of soil:
Epr ($mm\ h^{-1}$) $\leq$ Ib ($mm\ h^{-1}$)

13. Hours per irrigation position (Hp, h/position, Irrigation duration)

$$Hp \quad \frac{GWDA}{Epr}$$

14. Maximum Available daily irrigation hours in the system – Mah

The maximum irrigation hours per day possible to operate the irrigation system depends on:

The number of pumping hours
The available hours of the water source for the irrigation
The wind conditions
The availability of man power

15. Number of irrigation positions per day (Pd)

$$Pd \quad \frac{MAh}{Hp}$$

Pd = Number of positions/day (whole)

16. Irrigation hour per day (Hd)

Hd = Pd x Hp

17. Irrigation hour per cycle (Hc)

    $Hc = IrC \times Hd$

18. Irrigation positions per cycle (Pc)

    $Pc = IrC \times Pd$

19. Irrigated area per position (Iap, ha/position)

$$Iap \quad \frac{Nia}{Pc}$$

Nia = Net irrigated area per cycle (ha/cycle)

20. Gross water volume application per position (GWVAp, m^3/position)

    $GWVAp = Iap \times GWVA$

21. Required system discharge (Qr, $m^3 \ h^{-1}$)

$$Qr \quad \frac{GWVAp}{Hp}$$

22. Comparison between Qr with the available system discharge (Qs, $m^3 \ h^{-1}$)

    $Qr \leq Qs$

23. Number of emitters per positions (Emp)

$$Emp \quad \frac{Qr \times 1000}{qe}$$

24. Gross water volume application per irrigation cycle (GWVAc, m^3/cycle)

    $GWVAc = GWVAp * Pc$

25. Gross water volume application per cycle in orchards (GWVAc)

$$GWVAc \quad \frac{GWVA \times Np}{1000}$$

Np = Total number of plants in the net irrigated area (plants/Nia)

GWVA (plants) = Gross water volume application (l/plant)

26. Specific discharge (Qsp, $m^3\ h^{-1}\ ha^{-1}$)

$$Qsp \quad \frac{Qr}{\text{Total area}}$$

Qsp = Specific discharge (m^3/h/ha)
Qr = Required discharge (m^3/h)
A = Total area of the plot (ha)

WAY FORWARD

Climate change due to global warming is likely to cause shortage of water particularly in arid and semi-arid parts of India. The problem of shortage of water to rainfed crops could be resolved either by increasing total available water to crop plants or restricting evaporation losses relative to transpiration by integrating various management options like soil moisture conservation practices, water harvesting, manipulation in planting arrangement, fertiliser application, eliminating weeds, etc. In case of limited irrigation resources in arid regions, modest irrigation, deficit/extensive irrigation and pressurized irrigation exhibited the efficiency to improve water use and make efficient use of other resources like seed and fertilizer. For managing limited water supply some concepts like crop response factor as a tool to crop sensitivity rating, optimal leaf area concept, optimal yield concept, optimal irrigation scheduling, water use efficiency maximizing concept (protected agriculture), partial root zone wetting concept may be adopted. Adoption of these approaches will certainly lead to efficient management of scarce water in arid and semi-arid region. The incentives to the farmers in terms of research support, training and extension can help the farmers of arid region to reap the benefits. Further, area specific researches on these aspects are needed to provide proper package of practices to the ultimate users.

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GLOSSARY

Application rate (mm hr^{-1}) = $\frac{\textit{Sprinkler discharge (l/hr)}}{\textit{Sprinkler spacing (mxm)}}$

Application rate: Quantity of water applied to a given area in a given time - mm/hr. or cu. m/ha/hr

Discharge: Quantity of water that passes a given point during a given unit of time (or size of flow of water). Expressed as one cu.m./hour or liter/hour (1000 liters/hr = 1 cu.m./hour)

Frequency: Interval between irrigations; the time between the commencement of one irrigation cycle and the one that follows

Head of Water: The pressure at the base of a column of water and expressed in meters (10 meters = 1 atmosphere)

Irrigation Cycle: The time required to complete one irrigation of an area

Irrigation Intensity: The intensity of the impact of the drops of water striking the soil surface during irrigation. The intensity is dependent on the number of drops, size, velocity and angle of impact with the soil

Pipe Diameters: Aluminum pipes, soft or hard polyethylene pipes and rigid PVC- all sizes are expressed as outside diameters. Aluminum in units of inches and plastic in units of mm

Pressure: Force acting upon a surface. Expressed in units of kg cm^{-2} = 1 atmosphere

Quantity of water: Measure in units of volume. Cubic meters (cu. m) or liters (1000 liters = 1 cu. m)

Sprinkler Nozzle Diameters: Nominal sizes are expressed in mm. Nozzles that are not circular-size expressed as relative to circular nozzle with same discharge

Sprinkler Spacing: Distance between the sprinklers, along the laterals and between the laterals

Uniformity of application of water: Good distribution of water ensures that the soil is wetted to a uniform depth. Even distribution of water ensures uniform growth. On the other hand, faulty and non-uniform distribution will result in a shortage of water in some parts of the field and a surplus in other parts

Uniformity of Application Tests: A number of methods are used for testing the uniformity of application of sprinklers operating under varying conditions. In all the methods, irrigation water is collected in containers laid out in the plot. The size of the containers and their layout depend on the type of the sprinkler.

Coefficient of Uniformity of Application (Cu) in Accordance with Christiansen

Cu (%) = Coefficient of uniformity of application
Σ = Total
x_i = Individual reading – catch can
$\overline{x}$ = Mean readings – catch can
N = Number of containers (readings)

$$Cu\ (\%) = 100 \left[1 - \frac{\sum |x_i - \overline{x}|}{\overline{x}.n}\right]$$

$$Cu\ (\%) = 100 \left[1 - \frac{Sum\ of\ deviations}{Sum\ of\ reading}\right]$$

The minimum requirement for approving the use of sprinkler irrigation of field crops should be 84%.

Coefficient of Variation (CV)

An expression by calculating standard deviations in relation to the mean of the readings in %

$$CV\ (\%) = \frac{100}{\overline{x}} \sqrt{\frac{\sum (x_i - \overline{x})^2}{n}}$$

When the coefficient of application, Cu is > 80% a correlation exists between the two calculations:

$$CV\ (\%) \cong \frac{|100 - Cu(\%)|}{0.9}$$

Wind Speed: Unit measurement = meters per second (m/sec)

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