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HYDROLOGICAL BASIS OF A STRATEGY FOR SCHEDULING SUPPLEMENTARY IRRIGATION TO CEREAL CROPS IN DRYLAND AGRICULTURE

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Abstract

The yield of a dryland crop increases significantly on application of one or two supplementary irrigations at the critical periods of growth. The feasibility of providing two such irrigations on a regional scale to crops in the low rainfall (750 mm/yr) zone of the semi-arid tropical regions of India is examined. Annual rainy season recharge (deep percolation) of aquifers in the hard rock areas of peninsular India is assessed to be at least 50 mm. This provides one irrigation on an annually replenishable basis. Frequency analysis for various thresholds of runoff generating storm events from Hyderabad, Solapur and Anantapur and the actual runoff data of the alfisols and vertisols of Hyderabad suggest that a second captive irrigation of 50 mm is possible from runoff water harvested in farm ponds.

Four critical periods in crop growth—sowing, panicle *initiation, flowering, and grain-filling are considered to be most sensitive to drought stress. Any one of these periods is considered subjected to moisture deficit if the rainfall in the corresponding week is less than 20 mm.*

Rainfall events separated from each other by four weeks have been regarded as independent events and the probabilities of simultaneous occurrence of drought stress at all four, any three or any two of the stages of crop growth within a season have been determined for Hyderabad, Solapur and Anantpur. The probability that drought stress would occur in all four stages of crop growth within a cropping season is negligible for Hyderabad and Solapur. Interpretation of probabilities in terms of any three or any two stages requiring supplementary irrigation is also presented. Analysis of scenarios where sowing is done only after adequate rainfall or irrigation are given. A comparison of recurrence periods of drought stress for 20 mm/week and 40 mm/fortnight is presented and utility of probability analysis in the optimal scheduling of supplementary irrigation is described.

If water scarcity is the only constraint, then the present analysis suggests that the Kharif (rainy season) crop in Hyderabad can be stabilized and the yield increased with supplementary irrigations at two critical periods, the timing of which will vary from year to year. The possibility of Kharif cropping with two protective irrigations in the Solapur region is indicated. The effect of recurrent drought on crops in the Anantpur area can be reduced to once in 5-6 years if two optimally-spaced life-saving irrigations are provided.

Introduction

Water is one of the major limiting factors in agricultural development in the semi-arid tropics (SAT). Adequate and timely water supply assumes crucial importance in stabilizing crop yields and increasing their productivity in the semi-arid zones of India, where dryland farming is widely practised.

According to one estimate (Chaturvedi, 1976), the total water requirement of India by 2001 AD will be 15×10^9 m^3 and for agriculture (irrigation) alone it would be 13×10^9 m^3, while the total water potential, harnessable through current technology, may be only 9.27×10^9 m^3. Some other optimistic estimates put the harnessable potential level at 10.9×10^9 m^3 (Lahiri, 1975) and 11.3×10^9 m^3 (Padhye, 1983). These estimates indicate a wide gap between the projected need and the availability of water. This is a matter of serious concern to scientists, engineers, and planners.

Large parts of the SAT of India, besides being characterised by inadequate and unpredictable seasonal rainfall, are also underlain by hard rocks (mainly granites and basalts) that have inherently poor ground water potential. Thus the shortfall in water supply is acutely felt in this region, located in the States of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, and Tamil Nadu.

It is obvious that major research should be focussed on developing new technologies and better management practices to reduce the gap between the demand and supply of water, which is expected to increase during the next 15 years. New technologies and better management practices are required in order to :

- reduce evaporation losses,

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- augment ground water resources in the hard rock areas through artificial recharge,
- improve efficiency of water consumption of crops, and
- develop the conjunctive use of precipitation, surface, and ground waters.

The present paper deals mainly with the conjunctive use of rainfall, farm-harvested water, and ground water, and presents a theoretical basis for scheduling the limited irrigation water available.

Methodology

The following information is required to maximise benefits from the limited water reserves available for supplementary irrigation.

- Crop growth stages and critical periods (weeks) during which the crop (a cereal, *eg* sorghum) is most sensitive to drought stress.
- Benefits from supplementary irrigation in terms of crop stability and productivity.
- Captive sources of supplementary irrigation and the quantum available on an annual and replenishable basis.
- The rainfall pattern and the probability of occurrence of drought stress at critical periods of growth during a cropping season.

These aspects are illustrated through case studies of three representative stations in the low (undependable) rainfall area of the semi-arid tropics in India.

- Hyderabad (17° 27'N, 81° 08'E) having both alfisol (red) and vertisol (black) soil types and an average seasonal rainfall of 631 mm. The country rock is granite.
- Solapur (17° 40'N, 75° 54'E), representative of vertisol soils and having an average seasonal rainfall of 677 mm. The country rock is basalt.

- Anantapur (14' 41'N. 77° 37'E), having sandy alfisols and a seasonal average rainfall of only 502 mm. The country rock is mostly granite.

Crop Growth Stages and Critical Periods of Drought Stress

The stages of crop growth for cereals are germination, emergence, vegetative growth, flowering, and grain-filling. During particular stages the plants are more sensitive to shortage of water than at others. These are known as the critical or moisture-sensitive periods. Supplementary irrigation applied at these periods is more beneficial in terms of increase in yield than when applied at other periods. Drought stress during the critical periods considerably reduces crop yield which cannot be regained by subsequent application of water.

The moisture-sensitive periods differ with crop species and varieties and may differ for the same crop under different climatic and soil conditions. The periods and growth stages for various crops have been described in detail by Sankara Reddi (1976) and by Hiller and Howell (1983).

In this paper, three visible stages of crop growth are considered moisture-sensitive. In addition to these stages, the sowing stage can be considered critical from the point of view of irrigation scheduling, especially when emergence is endangered because of the delayed arrival of monsoons.

The four critical periods and related growth periods are as follows :

Critical period	Growth stage	Approx. time interval between two stages
I	Sowing	4 weeks
II	Panicle initiation	4 weeks
III	Flowering	4 weeks
IV	Grain filling	3 weeks

It is important to note that the four stages are sequentially separated by time-intervals of 3-4 weeks. The significance of this sequence in relation to irrigation scheduling is discussed below.

Benefits from Supplementary Irrigation

Dryland crops produce about 42% of food grains and 75% of oilseeds and pulses consumed in India (Venkateswarlu, 1982). Several examples of substantial increase in grain yield in response to supplementary irrigation have been described time and again, and only a few Indian examples are used to demonstrate the quantitative impact of supplementary/protective/life-saving irrigation on productivity in dryland farming.

Rajarathnam and Bagavandas (1961) reported that the yield of Kharif (rainy-season) sorghum at Coimbatore doubled on application of one protective irrigation. At Bangalore (Anon. 1984), one supplementary irrigation increased the yield of Kharif cowpea by 300%, giving an additional income of Rs 1300 per ha. Chowdhury (1979) reported that one life-saving irrigation increased the average yield by 122% in the case of 10 crops grown in different parts of India. Vijayalakshmi *et al* (1982) reported maximum increase in Kharif sorghum and pearl millet by 560% and 337% and for pigeonpea by 560% but a comparatively poor response in the case of groundnut where the yield increased by only 32%.

For the Rabi (post-rainy) season, the same authors (Vijayalakshmi *et al* 1982) report an increase by 123% for wheat, 113% for barley, 345% for safflower, and 116% for rapeseed sown at different research stations. Sivakumar *et al* (1979) recorded the grain yield of Rabi sorghum supplied with two irrigations as 5990 kg/ha as compared to 2430 kg/ha for non-irrigated sorghum at ICRISAT Centre. Hari Krishna (1983) recorded an increase of 414% for Rabi sorghum at Bellary, after two supplementary irrigations. Verma (1978) reported an increase of 133-225% with one application of irrigation and 284-411% with two applications in the yield of Rabi sorghum.

Two examples require separate mention because they indirectly bring out the importance of the application of irrigation at critical stages. In an experiment conducted at ICRISAT Centre during August 1974, (Anon, 1976), 50 mm of irrigation was applied to alfisol fields. For sorghum (at the grain-filling stage) and maize (pre-tassel stage), the irrigation came at critical periods in crop development, and therefore, both crops showed a yield increase of more than 100%. However, pearl millet showed an increase of 17-59% and sunflower 27-32%, probably because these crops were not in the moisture-sensitive period of growth. Similarly, Singh (1983) reports an experiment at Jodhpur in which grain yield of pearl millet, after one irrigation at critical period, increased by 337% during a drought year but the yield increase was only 7% in another year, because of a rainfall of 35 mm soon after irrigation.

These examples show a remarkable increase in grain yield because of one or two supplementary irrigations. They also show that unless the irrigations are well timed, the benefits are sub-optimal.

These results are from farm research stations where a small quantity (50 to 100 mm) of irrigation was applied under controlled conditions. The average farmer, however, uses all the water he can find and also cultivates water-intensive crops such as paddy and sugarcane whenever possible. There is thus a need to evolve incentives and simple guidelines for conservation and optimal use of the water resources, to enable farmers to benefit from these results.

Sources of Supplementary Irrigation

Irrigation derived from the water supply to the command areas of major irrigation projects has limited scope in the semi-arid regions of India. As stated in the VIth Plan document (Anon, 1981), only 25% of the total cropped area is irrigated, and farmers in the remaining areas continue to depend on rainfall. An estimate of the need for and availability of water by 2001 AD, quantified by various States (Chaturvedi, 1976), indicates that the total area under major irrigation is not likely to increase considerably in most of the southern states, with the probable exception of Andhra Pradesh. The importance of even small amounts of life saving irrigation in improving the yield of rainfed crops is amply demonstrated. It is therefore, necessary that the existing captive sources of supplementary irrigation, harnessable on a farm, need to be quantitatively evaluated and developed. Two such sources are ground water and the recently advocated farmponds.

Ground Water

Ground water is a dynamic resource which is annually replenished. The replenishment takes place primarily through percolation of a fraction of the precipitation to aquifers, after passing through the unsaturated soil zone. Ground water recharge also occurs through seepage from lake and tank beds, channel floors and through the return flow of some of the water applied in irrigation.

Most of the semi-arid southern regions of India are covered with hard rocks such as granites and basalts that have poor permeability. Further, the annual evapotranspiration (potential evapotranspiration) is much higher than the precipitation in this area (Rao *et al*, 1976). As a result, annual ground water recharge is lower in these regions than in alluvial area, where the geological formations have much higher permeability and storage capacity.

The National Geophysical Research Institute at Hyderabad has estimated the annual ground water recharge for some basins in peninsular India (Athavale, 1985). Figure 1 shows the location of the recharge measurement basins. The average values of recharge due to precipitation, determined for one hydrological cycle, are listed in Table 1. Tritiated water was injected in the soil at a depth of about 80 cm before the onset of the rainy season. Vertical soil profiles, sampled at intervals of 10-20 cm, were collected from the injection site at the end of the rainy season and at the end of the hydrological cycle. The Tritium and moisture content of each sample were measured in the laboratory and plotted against depth. The displacement of the tracer peak due to vertical percolation was noted. The water content of the column between the injection point and the displaced depth of the tracer represented the recharge at a particular site.

The mean values of recharge obtained from several site-specific values in each basin varied between 39 and 100 mm (Table 1).

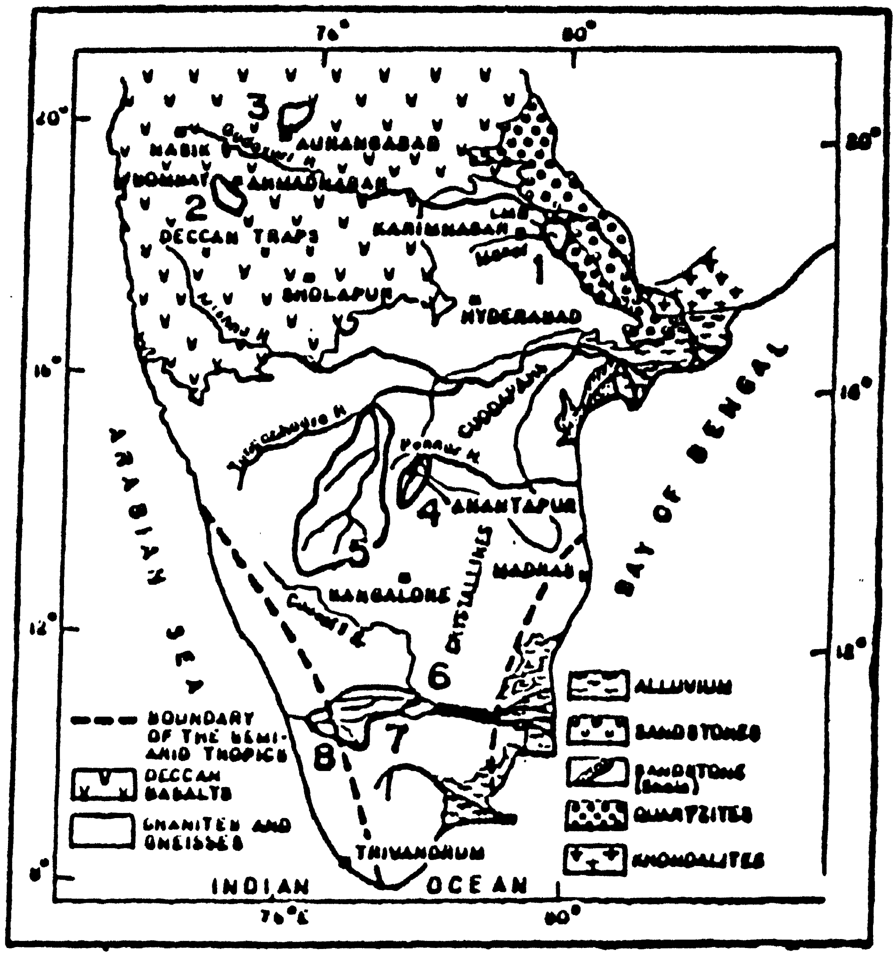

Fig. 1 Geological map of semi-arid India showing recharge measurement basins

nce the basins investigated are well distributed over the semi-arid gion of peninsular India, the mean values of annual recharge are nsidered to be fairly representative of this region. They also ow that for low-rainfall areas (<750 mm per year) the average charge is about 50 mm. This value is minimal since it represents tural recharge due to precipitation alone. Additional recharge kes place through tanks and the return flow of irrigation but antification of this component is not available. Further, 50 mm the average recharge due to precipitation for the entire area. As exploitation of ground water occurs in the cultivated area of ni-arid India (50% of total), the recharged water, transferred m nearby uncultivated areas in a watershed, is also used. Thus total quantum of ground water available for use in supplemen-

TABLE 1

Recharge Measurements in Basins in Semi-arid Tropical India Using Injected Tritium Technique
(see also Fig. 1)

Sl* No	Location	Geological formations	No. of measurement sites	Average rainfall (mm)	Mean Recharge (mm)
1	Lower Manner basin	Sandstone, shale, quartize, dolomite, granite	26	1250	100
2	Godawari-Purna basin	Basalt	24	652	56
3	Kukadi basin	Basalt	19	612	46
4	Marvanka basin	Granite, gneiss, schists	19	550	42
5	Vedavati basin (West Suvarnamukhi sub-basin)	Granite, gneiss, schist	19	565	39
6	Noyil basin	Granite, gneiss, schist	21	715	69
7	Vattamalaikarai basin	Granite, gneiss, schist	2	460	61
8	Ponnai basin	Granite, gneiss schist	9	1320	61

*The serial numbers correspond with the numbers assigned to basins in Fig. 1.

tary irrigation, on an annual basis, could be more than 50 mm. However, only 70-80% of the recharge water is considered recoverble. Losses also take place at the stage of application of irrigation. Thus, 50 mm of ground water is the minimum quantity available for irrigation in the rainfed farming areas in peninsular India.

Farm Ponds

Farm ponds are small-size excavations on a farm, positioned to collect runoff or drainage water with the intention of utilising it for supplementary irrigation or for augumenting ground water reserves through percolation. These water-harvesting and recycling structures have come in vogue over the last decade (Singh, 1982). Farm ponds have been excavated at ICRISAT Centre, agricultural university research stations and in model watersheds studied by the Indian Council of Agricultural Research (ICAR).

A farm pond, in general, has a capacity to store 250-1000 m^3 of water. Farm ponds constructed in light soils lose water through seepage and thereby augument ground water. Methods for minimizing seepage with low cost sealing agents have been suggested (Vijayalaxmi *et al*, 1982; Maheshwari, 1981; and Dwivedi and Sarkar, 1983). For simplicity, we assume that farm ponds are used for direct application of irrigation water.

The feasibility of having 50 mm of water available for one irrigation to a farm, from the water collected in its own pond, is examined here in the case of the three locations mentioned.

Data on daily rainfall for these stations were analysed to study the frequency of runoff-generating storms (Table 2). The total number of storms above threshold values of daily rainfall of 30 mm, 40 mm, 60 mm, 80 mm, 90 mm, and 100 mm are listed along with the average number of such storms in a rainy season.

Pathak et al (1985) consider that a threshold at 30 mm per day is necessary for the initiation of runoff. They also show that a storm giving 90 mm or more of rainfall, would account for 75-91% of the seasonal runoff from cropped vertisols and 31-66% from alfisols.

Hanumantha Rao (1983) considers 25 mm as the minimum level for runoff generation. However, data about variation of runoff depth with different thresholds of storm precipitations, such as those listed in Table 2 are lacking. Assuming therefore, that rainfall of 60 mm and above would produce significant runoff, the presentation in Table 2 shows that at least one such event occurs at each of the three stations during the year.

The total number of events contributing towards runoff *ie* >30mm) is, on average, six per year at Hyderabad and Solapur and five per year at Anantapur.

Antecedent rainfall is an important parameter in assessing the runoff generated by a given event. For the same rainfall the percentage runoff is greater in the later months of the rainy season because the soil profile is already saturated. In Table 2, the number of events taking place during the later monsoon months are also shown separately for the >60 mm threshold. These data indicate that about 50% of the >60 mm storms at all three stations occur during the months of August and September.

In the case of fallow vertisol and Kharif-cultivated alfisols, El-swaify *et al* (1985) found that the average runoff over a five year period (1976 to 1980) was above 200 mm or approximately 25% of the precipitation, while the average runoff from a Kharif-cropped vertisol watershed was about 100 mm.

Runoff measurements for catchment areas of various sizes, within a semi-arid basin, show that the depth of runoff decreases with increase in the size of the catchment area (Boughton and Stone, 1985) due to transmission losses and storage in interevening natural depressions. This study indicates that losses are insignificant for small farm-size watersheds (of 1-10 ha) ; however, for larger catchments, the mean annual runoff is reduced by about 38% for every 10 fold increase in catchment area. A farm pond is therefore, an optimal-sized reservoir used for efficient collection of runoff water for supplemental irrigation.

The data on runoff suggests that it is possible to collect sufficient runoff water in lined farm ponds for one supplementary irrigation

TABLE 2

Runoff-generating Daily Rainfall Events During June-October at Hyderabad, Solapur, and Anantapur, at Six Threshold Levels (mm). (Events in August/September are also shown separately for the >60 Threshold)

Station	Database	>30 mm		>40 mm		>60 mm		>80 mm		>90 mm		>100 mm	
		Total no.	Av/year	Total no.	Av/year	Total no.	Av/year	Total no.	Av/year	Total no.	Av/year	Total no.	Av/year
Hyderabad	70 years (1901-1970)	428	6.20	248	3.59	80	1.14	30	0.43	23	0.33	13	0.19
	Events during August+September					38							
Solapur	41 years (1930-1970)	258	6.29	156	3.80	58	1.41	26	0.63	26	0.39	14	0.34
	Events during August+September					30							
Anantapur	74 years (1911-1984)	387	5.30	240	3.29	98	1.32	38	0.52	20	0.27	16	0.22
	Events during August+September					51							

Av=Average

of 50 mm, even after accounting for losses due to evaporation, seepage, and collection-application inefficiency. Selvarajan *et al* (1984) have demonstrated the technical and economic viability of one such farm pond in the vertisal covered Bellary area, having an annual rainfall of 508 mm. However, to verify and generalise these preliminary findings, detailed rainfall-runoff analysis and simulation studies, along with further experimentation at sites in low-rainfall areas are necessary.

Probability of Simultaneous Occurrence of Drought Stress at Critical Periods in a Cropping Season

The preceeding discussion indicates that a minimum of two supplementary irrigations of 50 mm would be available, whereas a cereal crop may have four critical periods in its growth cycle that are susceptible to drought stress. The water resource thus seems inadequate when compared to the crop water requirement. Probability analysis of the conditions, wherein drought stress would develop at all four, any three, or any two of the critical periods in a cropping season, has therefore, been carried out, using daily rainfall data.

Probability analysis of daily rainfall for Hyderabad and Solapur has been carried out by Stern *et al* (1982). Virmani *et al* (1982) have worked out the weekly rainfall probability for Hyderabad, Solapur, Anantapur and many other India Meteorological Department's gauging stations for threshold levels of >5 mm, >10 mm, and >20 mm. They have tabulated, for standard weeks, the initial probability of a wet week, and the conditional probability of a wet week following a wet week and a wet week following a dry week.

A week having a rainfall of at least 20 mm can be considered as a week with assured rainfall (Bala Subramanian *et al* 1982). In the following analysis, this threshold value has been adopted. The probability for rainfall less than 20 mm during a week was derived for selected weeks for the three stations, from the weekly probabilities computed by Virmani *et al* (1982). These are listed in Table 3. It is assumed in the ensuing analysis that any week having less than 20 mm of precipitation is likely to generate drought stress during a critical period in crop growth.

For Kharif cereal crops at Hyderabad and Solapur, the following four standard weeks, commencing with the 3rd week of June, have been chosen to represent the critical periods.

Critical period	Growth stage	Standard week	Dates
I	Sowing	24	11-17 June
II	Panicle initiation	29	16-22 July
III	Flowering	33	13-19 August
IV	Grain-filling	36	3-9 September

For Anantapur, the analysis has been done for three sowing weeks: 24 (11-17 June), 26 (25 June to 1 July), and 28 (9-15 July). The time interval between the growth stages was kept the same in each case.

The four critical periods are separated from each other by a period of 3-4 weeks, and interdependence of rainfall events occurring in these periods is highly unlikely. Detailed forecasting of weather for more than 2 weeks is not possible (Smith, 1975; Marchuk, 1979). We have, therefore, considered the rainfall events corresponding with growth-stage weeks as independent events.

The probability of the simultaneous occurrence of such independent events can be obtained through simple multiplication of their discrete probabilities (Haan, 1977). In Table 3, the discrete probabilities for Hyderabad, Solapur, and Anantapur are listed, and the probabilities of the simultaneous occurrence of drought stress at all four, any three, or any two critical periods are given in Table 4. A similar analysis was carried out in each case, for probability of rainfall less than 40 mm, over a period of 2 consecutive weeks for the same growth stages (Table 5). The purpose of this analysis was to see if the resulting data could favourably enlarge the scope of management options in irrigation scheduling.

TABLE 3

Rainfall Probabilities for Selected Weeks at Hyderabad, Solapur and Anantapur

Station	Probability of rainfall <20 mm in a week			Probability of rainfall <40 mm in 2 consecutive weeks		
	Std week	Period	Probability	Std week	Period	Probability
Hyderabad	24	Jun 11-17	0.61	24-25	Jun 11-24	0.49
	29	Jul 16-22	0.33	29-30	Jul 16-29	0.23
	33	Aug 13-19	0.52	33-34	Aug 13-26	0.43
	36	Sep 3-9	0.48	36-37	Sep 3-16	0.46
Solapur	24	Jun 11-17	0.53	24-25	Jun 11-24	0.34
	29	Jul 16-22	0.37	29-30	Jul 16-29	0.34
	33	Aug 13-19	0.63	33-34	Aug 13-26	0.54
	36	Sep 3-9	0.53	36-37	Sep 3-16	0.44
Anantapur	24	Jun 11-17	0.85	24-25	Jun 11-24	0.89
	26	Jun 25-Jul 1	0.78	26-27	Jun 25-Jul 8	0.84
	28	Jul 9-15	0.85	27-28	Jul 2-15	0.88
	29	Jul 16-22	0.75	29-30	Jul 16-29	0.75
	31	Jul 30-Aug 5	0.75	31-32	Jul 30-Aug 12	0.79
	33	Aug 13-19	0.66	32-33	Aug 6-19	0.77
	35	Aug 27-Sep 2	0.71	33-34	Aug 13-26	0.66
	36	Sep 3-9	0.66	35-36	Aug 27-Sep 9	0.70
	37	Sep 10-16	0.64	36-37	Sep 3-16	0.56
	38	Sep 17-23	0.44	38-39	Sep 17-30	0.32
	40	Oct 1-7	0.51	39-40	Sep 24-Oct 7	0.45

Std week=Standard week

TABLE 4

Percentage Probability of the Simultaneous Occurrence of Drought Stress (Rainfall <20 mm/week) in all Four, any Three, or any Two Critical Periods During Crop Growth. (The Probabilities of Scenarios in which Sowing is done after Adequate Rainfall or Irrigation are Indicated in Parantheses)

Station	All four stages	Any three stages	Any two stages
Hyderabad Sowing 24th week	5.0 (–)	15.0 (7.5)	32.0 (25.0)
Solapur Sowing 24th week	6.5 (–)	17.7 (11.0)	33.4 (33.4)
Anantapur			
(a) Sowing 24th week	30.7 (–)	46.5 (36.1)	63.8 (54.8)
(b) Sowing 26th week	18.2 (–)	41.5 (24.3)	58.5 (53.3)
(c) Sowing 28th week	18.3 (–)	35.3 (21.5)	56.1 (42.2)

TABLE 5

Percentage Probability of the Simultaneous Occurrence of Drought Stress (Rainfall <40 mm in 2 Consecutive Weeks) at all Four, any Three, or any Two Critical Periods in Crop Growth. (The Probability Figures in Parantheses Represent Situations where Sowing is Done only after Adequate Rainfall or Irrigation)

Station	All four stages	Any three stages	Any two stages
Hyderabad Sowing 24-25th week	1.7 (–)	7.6 (3.6)	21.1 (15.5)
Solapur Sowing 24-25th week	2.7 (–)	7.6 (3.6)	23.8 (23.8)
Anantapur			
(a) Sowing 24-25 week	24.7 (–)	44.1 (27.7)	66.8 (49.5)
(b) Sowing 26-27 week	14.9 (–)	46.5 (17.7)	66.4 (55.3)
(c) Sowing 27-28 week	17.0 (–)	37.9 (19.4)	67.8 (43.1)

A Strategy for Scheduling Supplementary Irrigation

The simultaneous drought occurrence probability data, given in Table 4 is based on discrete probabilities of weekly rainfall of <20 mm (Table 3). It can be directly utilised in taking decisions about irrigation application in a cropping season. This is explained below in discussion about Kharif cropping for each station. A tacit assumption in this discussion is that water scarcity is the only constraint affecting the grain yield. In reality, however, other factors such as soil fertility and physical characteristics, crop variety, cropping system, and the incidence of weeds and pests affect the yield.

Hyderabad: The probability that drought stress (rainfall <20 mm in a week) would occur simultaneously at all the four critical periods in crop growth, works out to be only 5%. In terms of the recurrence period it means that such a situation will arise only once in twenty years. Such a probability, therefore, need not be taken into consideration when irrigation options are being assessed.

The maximum probability of drought stress occurring simultaneously in any three critical periods is 15%. This means that if irrigation is applied at two critical periods, low productivity would occur only once in six or seven years.

The maximum probability of drought stress occurring simultaneously in any two critical periods is 32% or once in 3 years. Therefore, to stabilise crop growth, two irrigations would be required only once in three years, and one supplementary irrigation only, or none, would suffice for the other two years. This analysis indicates that Kharif crops in the Hyderabad area can be stabilized with two optimally-timed irrigations, the timing of which would have to be decided on a year-to-year basis. Whenever one irrigation is found to be adequate for the Kharif crop, the second irrigation can be kept in reserve for the Rabi crop.

At present, farmers in the Hyderabad area sow only after adequate rainfall. In such a situation, the probability that simultaneous

drought stress will occur in the next three or any two subsequent critical periods are further lowered to 7.5% and 25% respectively (Table 4). Sowing after sufficient precipitation implies that the actual date of sowing is not necessarily in the 24th week as chosen for our analysis. However, as long as the various critical periods remain staggered as in our model, the probability analysis and conclusions therefrom should remain broadly valid.

Solapur: The probability that drought stress will occur in all four critical periods is low (6.5%), or statistically insignificant. The probability in any three periods is 17.7% or once in six years, while the probability of a drought situation requiring the application of two irrigations would occur once every three years.

Solapur represents a large tract of vertisols in India, that are followed during the rainy season: an area of 18×10^6 ha within a total vertisols area of 60 million ha (Hari Krishna, 1983). A major factor leading to this practice is the delayed arrival of the rainy season. Assuming a scenario of presowing irrigation, the prababi-lity of simultaneous drought stress in two or all three subsequent critical periods are indicated in Table 4. The probability that drought stress will occur in all three periods in such a scenario is 11%, or once in nine years, while that for only two stages remains the same (33.4%). This means that two more irrigations will be required every third year. If a third irrigation is possible, either independently from ground water or from farm pond or through their combined use once every few years, then the possibility of Kharif cropping in these areas can be considered.

Anantapur: The total rainy season rainfall at this station is much lower than at Hyderabad and Solapur, and it has a higher coefficient of variation. From three different sowing weeks considered the 28th week appears least unfavourable. But even in this case the probability that drought stress would occur in all four critical periods is once every five or six years, and this situation is beyond amelioration with only two irrigations. The probability that drought stress would occur in only one period after application of two irrigations is once every three years, and that for stress occuring in two critical periods would be every alternate year.

This means that, even on application of two irrigations, low yield would be expected every 3rd year, and poor yield every 5th or 6th year.

Where sowing has been carried out after adequate rainfall in the 28th week, the probability of drought stress occuring in all three subsequent critical periods is reduced to once in five years while that for two periods is effectively unchanged.

Comparison Between Two Consecutive Weeks (<40 mm) and one Week (<20 mm) Probabilities

Tables 4 and 5 suggest that the probability that drought stress would occur in each group of critical periods in the case of rainfall at <40 mm in two consecutive weeks is comparatively low. This is further brought out in Table 6, which lists the recurrence periods for each grouping for all three stations. Data for Hyderabad and Solapur show a substantial increase in the recurrence period in the <40 mm case, as compared to the <20 mm/week case, while at Anantapur no such advantage can be perceived. It follows that, at least in the case of Hyderabad and Solapur, use of varieties having a capacity to tolerate drought over a period of two weeks would improve crop stability. Further, the time range for a decision about the application of supplementary irrigation would also be doubled.

Conclusions

1 Available experimental data suggest that one life-saving irrigation can significantly improve the yield of dryland crops.

2 Ground water recharge masurements carried out in several basins in semi-arid tropical India suggest that one supplementary irrigation of 50 mm can, in principle, be obtained from well-withdrawals on an annual and sustainable basis.

3 Storm frequency data for three low-rainfall area stations Hyderabad, Solapur and Anantapur—indicate that about five or six runoff—generating events occur during each rainy season and at

TABLE 6

Comparison of Recurrence Periods (in years) of Moisture Stress, for Precipitation Levels : <20mm/Week and <40mm/Fortnight (Derived from Tables 4 and 5)

Station	All four stages No. of years		Any three stages No. of years		Any two stages No. of years	
	<20mm	<40mm	<20mm	<40mm	<20mm	<40mm
Hyderabad	20.0	58.8	6.7	13.2	3.1	4.7
Solapur	15.4	37.0	5.6	10.5	3.0	4.2
Anantapur (sowing in 28th week)	5.5	5.9	2.8	2.6	1.8	1.5

least one of them has an intensity of >60 mm/day. Runoff generation from such storms can, in theory, accumulate enough water in farm ponds to provide a second supplementary irrigation of 50 mm.

4 The probability that drought will occur in all four critical periods in the cropping season is insignificantly low at Hyderabad and Solapur, and is about 18% for Anantapur.

5 If water is the only constraint, Kharif cropping in the Hyderabad area can be stabilized, and can become feasible in the Solapur area, with the application of only two protective irrigations at specific critical growth periods in which drought stress occurs.

6 In the Anantapur area, even after the application of two supplementary irrigation, losses of yield or even crop failure, once every 5-6 years, and marginal yields every 3rd year, are predicted.

7 A comparison of probabilities for the simultaneous occurrence of drought for rainfall levels at <20 mm/week and <40 mm/fortnight suggest that crop stability will improve, in general, if seed varieties capable of withstanding drought stress over a period of 2 weeks are used.

General Remarks

This paper describes a conceptual framework for the adoption of supplemental irrigation on a regional scale in dryland farming in India. Details in terms of technical feasibility and actual practices will vary from place to place, and there is a need for validation in selected watersheds. Aquifers in hard rocks are heterogenous, and the equitable distribution of water from successful wells may be necessary. Dependability of farm ponds will have to be demonstrated, and possibly, farm ponds and other devices for retaining runoff and for augumenting ground water recharge may prove to be more effective in storing water and making wells more remunerative. In such a situation the entire question of timing the application of irrigation would be simplified. Composite watershed management, comprising efficient collection of runoff, better maintenance of traditional storage structures, the construction of mini-percolation tanks for augmenting ground water recharge, and the scientific exploration for well sites, will have to be adopted (von Oppen, 1985). There is also a need to disuade farmers from cultivating water-intensive cash crops.

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