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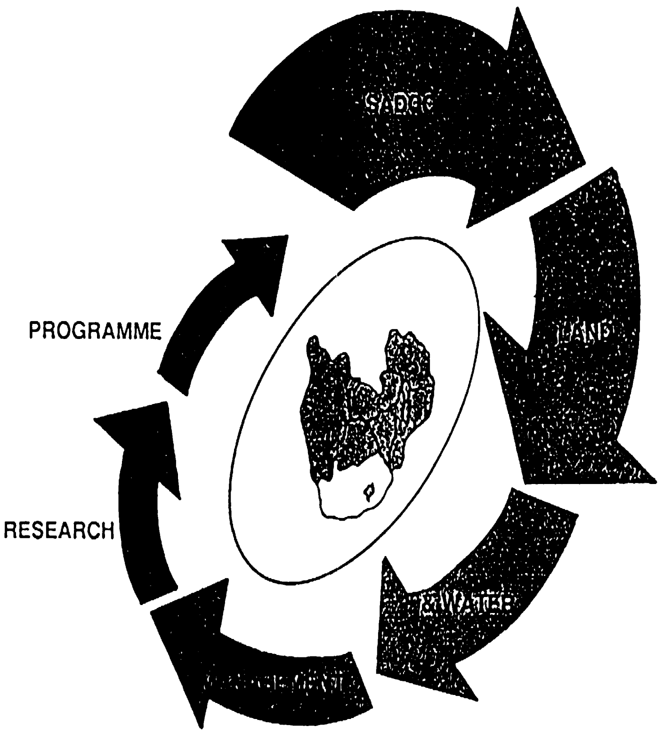

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Prospects of Water Harvesting and its Utilization for Agriculture in the Semi-Arid Tropics

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ABSTRACT

The average annual rainfall in some parts of the semi-arid tropics is sufficient for raising one or in some cases, two good crops in a year. However, the onset of rainfall and its distribution are erratic and prolonged droughts are frequent. Most of the rain occurs as high intensity storms resulting often in sizeable runoff volumes. High rainfall intensities coupled with incomplete ground cover and unstable soil structure favour runoff collection in these areas.

There is considerable evidence that the yield of dryland crops can be increased and stabilized with one or two supplemental irrigations at critical periods of growth. The feasibility of providing such irrigation from stored runoff is examined for two watersheds at ICRISAT Center. The utility of a model developed to estimate runoff is demonstrated. The probabilities of getting a certain amount of water from the runoff harvesting system during the drought stress at critical periods in crop growth were determined. Results from these analyses show that runoff harvesting in small tanks for supplemental irrigation has a potential impact on crop production on some watersheds.

This paper also describes ICRISAT's experience in runoff collection, seepage and evaporation control methods for small tanks and supplemental irrigation for different cropping systems. Studies at ICRISAT and elsewhere have shown clearly that crop yields, particularly on Alfisols can be increased through timely supplemental irrigation when there is drought during the rainy season. On Vertisols, runoff harvesting and supplemental irrigation have been found to be less feasible and less profitable than on Alfisols. However, an economic evaluation using a simulation model has indicated that supplemental irrigation is a viable and attractive proposition in Vertisol areas receiving more than 1000 mm rainfall, provided tank seepage is low. This result from the simulation model remains to be evaluated in field studies.

INTRODUCTION

The central problem of water supply for agricultural production is that natural precipitation does not always occur at the right place and/or at the right time. This phenomenon is greatly magnified in the semi-arid tropics (SAT). Traditional methods to correct this problem have been to build storage reservoirs or drill wells. These measures are often not possible in the developing countries of the SAT because they are either financially or geologically infeasible due to insufficient aquifers and lack of satisfactory reservoir sites. (Sharma and Helweg, 1982). In some instances farmers have tried to solve water shortage problems by using traditional methods that have shown more promise than those used in developed countries. These traditional methods may often be improved by using new skills and knowledge.

In parts of SAT India, "tanks" are traditionally used to harvest water. Tanks are small reservoirs, located either behind small earth dams or are ponds excavated out of a field to collect runoff during the rainy season for use when there are prolonged droughts in the rainy season and/or for use in the dry season. However, because of high evaporation due to large water surface area and sometimes large seepage losses, only a small quantity of water is usually available from these traditional tanks for irrigation. Furthermore many of these traditional tanks have lost storage capacity because of siltation. The ratio of the command area to the submerged area is often less than 3. It is therefore necessary to reinvestigate this old concept in the light of present technology for construction of tanks. Increasing the water-use efficiency through timely irrigation, proper selection of crops and cropping systems and efficient design and construction of tank are essential prerequisites to realizing maximum benefits.

In this paper, we review work conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and elsewhere on the design and construction of tanks with minimum seepage and evaporation losses and the use of water stored in them to supplement rainfall during drought periods. The prospects of water harvesting on two watersheds at ICRISAT Center and the economic evaluation of tank systems using simulation models are also discussed.

Design and construction of small tanks

Most of the farms in rainfed areas in India are small. Unless the farmer whose land generates runoff receives the benefits accruing from runoff storage units, it will be difficult to encourage the adoption of small tanks. The following points are essential in the design and construction of small reservoirs:

Criteria for site selection: In choosing the site for a tank, suitable topography that would give large storage to excavation ratios should be selected. Natural depressions, valleys, gullies or elevation differences between two fields should be utilized.

Design criteria for small tanks: A high storage efficiency (i.e. water used for irrigation divided by total water stored) of collected runoff is very desirable. The design should aim to reduce two main losses viz. seepage and evaporation. In order to reduce seepage, the ratio of the wetted surface area in relation to the quantity of water stored should be small. Evaporation losses can be minimised by deep rather than shallow storage structure.

A total of 13 tanks of different designs and specifications were constructed at ICRISAT center in the 1970s. The cost of construction of these tanks averaged Rs. 10 $(m^3)^{-1}$ (1 US$=17.6 Rs.) of water storage while the land area occupied by them varied between 3 and 13% of the catchment area. The storage capacities and area occupied by the tank ranged between 0.1-1.2 ha-m and 0.2-0.8 ha respectively. The storage efficiency was between 1.4 and 2.65 (Sachan and Smith 1987). A distinctive feature of these tanks is simple outlet structures (Fig. 1.). Sharma and Helweg (1982) developed a method for optimally designing and locating a small tank in a catchment. Their computations were based on irrigation demand of a crop, fixed losses in the tank, losses from the tank, cost of land under the tank bed, cost of irrigation, seasonal runoff expected and other catchment descriptions such as area and length.

Assessment of water availability in tanks

Depending on the balance between the magnitude of runoff from catchment compared with seepage and evaporation losses, water may or may not be available in required quantities at the time it is most critically needed. Two tanks located on Alfisols in RW1 and RW3D watersheds at ICRISAT center were selected to determine the losses and water availability. Rainfall, and open pan evaporation recorded for 30 years (1958-1987) were used in this analysis. A runoff model based on modified curve number method and a soil moisture accounting procedure (Pathak *et al.* 1989) was used to simulate the daily runoff and soil moisture for RW1 and RW3D watersheds. The daily net inflow and outflow from the tank were calculated by substracting daily evaporation and seepage losses from the watershed runoff. Based on the net inflow or outflow estimations, daily available water in the tank was calculated. The probabilities of getting 40 mm of water for supplemental irrigation from the tanks on RW1 and RW3D are shown in Fig. 2. It is observed from Fig. 2 that the probability of getting 40 mm water for irrigation from the tank located on RW1 is large for the major part of the growing season. Because of relatively large seepage rate and low runoff from RW3D watershed, the probability of obtaining 40 mm water for irrigation is not very good. The conditional probabilities of availability of 20 and 40 mm water in the tank for irrigation during periods of drought were also calculated for the tanks on RW1 and RW3D. For simplicity, drought was assumed to occur when the available moisture in the root zone fell below 30% of the water holding capacity of the soil.

The conditional probabilities of the availability of 20 and 40 mm of water from tanks during the periods of drought were found to be generally larger than those shown in Fig. 2. On RW1, the probabilities of the tank having 40 mm water for supplemental irrigation during drought periods in July was 68% while in August and September, the probability exceeded 91%. The conditional probabilities of having 20 mm of irrigation water during drought periods in July, August, September and October exceeded 97%.

Probabilities of occurrence of drought stress in 3 crop growth stages *viz.* growth stage 1 (GS1, sowing to panicle initiation), growth stage 2 (GS2, panicle initiation to anthesis) and growth stage 3 (GS3, grain-filling stage) were estimated. In addition, the probability of obtaining 40 mm of water for irrigation from tanks during the drought stress period for each crop growth stage was calculated. It was found that the chances of 40 mm of water being available from the tank during drought periods of GS2 and GS3 exceeded 90% compared with 68% for GS1.

Considerable information on various aspects of water storage in tanks can be obtained by using the runoff model (Pathak *et al.* 1989). The model can estimate the probability of runoff and water availability in a tank when long term daily rainfall and open pan evaporation records are used as input data. The chances of adequate stored runoff water being available for supplemental irrigation during moisture stress periods can also be determined.

A complete analysis of the impact of water harvesting on crop growth and yield can be obtained by combining the output from the runoff model of Pathak *et al.* (1989) with a simple crop yield model such as the RESCAP model developed at ICRISAT (Monteith *et al.* 1989). Such models can be used to estimate the expected increase in crop yields as a result of supplemental irrigation and also help in developing a strategy for scheduling supplemental irrigation particularly in cases where there is more than two drought stresses in a season. This aspect of work is presently under consideration.

Minimizing losses from runoff storage facilities

Seepage and evaporation losses associated with small reservoirs are the two main reasons negating their technical acceptability and the cause of low storage efficiency, thus making water harvesting expensive. This section reviews some of the work done on seepage and evaporation control methods.

Minimising seepage losses

A major problem associated with large seepage rates of tanks is that there may be little or no water available at the critical growth stages of the crop. Seepage losses can be reduced by selecting locations having sub-soils with low permeability and by minimising the wetted perimeter of the tank. Seepage losses can also be minimised by selecting an appropriate depth of the tank based on the thickness of the subsoil.

Early studies at ICRISAT showed that a lining of the tank bed and bund slopes with asphalt 4 l $(m^2)^{-1}$ reduced seepage of tanks located on deep Alfisols from 97% to 47% when compared with an unlined tank (24.7 to 50 mm d^{-1}). On Vertisols, there was no significant reduction in seepage rates for tanks lined with asphalt. A seepage reduction of about 70% was obtained with a treatment of Na_2CO_3 + straw on Vertisols (ICRISAT, 1976). However, the use of straw presented a problem after some time because its decomposition resulted in a porous structure of the lining. In another study, linings of clay + silt + Na_2CO_3 and clay + CaCl + $CaCO_3$ at ratio of 20:5:1 were successfully used to reduce seepage by 55%. It was found that soil cracks were the major problems in Vertisols in addition to the necessity to reapply the chemicals after every 3-5 years.

The progress of studies on cheap, locally available seepage- control materials on various research stations in India has been quite satisfactory. On Alfisols, soil + cement + bentonite mixture has been reported to be promising. At a few places, plastering the surface of the storage area with soil + cow dung + straw has been found to give good results. Soil, sand, cement (4:4:1) mixture of 2.5 cm thickness has also been reported to be effective and economic (Subramaniyam *et al.* 1976).

Maheshwari (1981) experimented with soil dispersants, and soil cement lining as two basic methods to reduce seepage rates on Alfisols and Vertisols. Performance of some of the lining materials on Alfisols and Vertisols are given in Table 1. Soil- cement was the most effective lining on Alfisols. The seepage rate of soil-cement lining was as low as 8.2 l $(m^2)^{-1}$ day^{-1}, giving a reduction in seepage of 97.2%. However, cracking was found to occur when the tank was emptied and the lining exposed to the sun thus increasing the seepage rates when the tank was refilled.

Minimising evaporation losses

Evaporation losses can be minimised by designing a tank which has minimum exposed surface area. Very little success has been obtained by retarding evaporation from exposed surface. As far back as 1960, major attention was given to the application and utility of various combinations of monomolecular layers or films of long chain alkanols (Margin and Randall 1960). Results from most of the studies with alkanols have been discouraging, evaporation was reduced by only 10% to 35% in field tests. Cooley and Meyers (1973) demonstrated that evaporation losses can be reduced from 87% to 33% with the use of reflectance such as foamed wax blocks. Unfortunately, all the materials used for increasing reflectance have so far been of theoretical interest and cannot be recommended owing to their high costs. For the semi-arid tropics where capital resources are very meagre, locally available cheap sealants will have to be found. At ICRISAT we have tried to minimize the exposed water surface of tanks by deepening and utilizing stored water early in the season as strategies to reduce evaporation losses.

Response of crops to supplemental irrigation

Benefits of supplemental irrigation in terms of increasing and stabilizing crop production have been impressive even in dependable rainfall areas on both Alfisols and Vertisols. Striking benefits have been reported from supplemental irrigation on Alfisols at ICRISAT (El-Swaify *et al.* 1985; Pathak *et al.* 1986) and elsewhere (Hedge *et al.* 1981; Vijayalakshmi 1983). As shown in Table 2, good yield responses to supplemental irrigation were obtained on Alfisols in both rainy and postrainy seasons. The average water application efficiency, WAE (ratio of increase in yield to depth of water applied) for sorghum (14.8 kg mm^{-1} ha^{-1}) was larger than that for pearl millet (8.7 to 10.1 kg mm^{-1} ha^{-1}). An intercropped pigeonpea responded less to irrigation and its average WAE ranged from 5.3 to 6.7 kg mm^{-1} ha^{-1} for both pigeonpea/sorghum and pigeonpea/pearl millet systems. Tomatoes responded very well to water application with an average WAE of 186.3 kg mm^{-1} ha^{-1}.

Table 1 Performance of different linings in experimental tanks on Alfisols and Vertisols, ICRISAT Center

Lining treatment	Bulk density of lining g cc^{-1}	Seepage rate Lm^{-2} day^{-1}	Seepage (when compared with control) %
Alfisols			
1. Control (without) lining	N.O.*	290	-
2. Alfisol + coarse aggregate (1:1)	1.64	145	50
3. Alfisol (compacted)	1.62	115	40
4. Alfisol + Vertisol (1:2)	1.73	27	10
5. Soil cement (10:1)	N.O.	8	3
Vertisols			
1. Control (without any lining)	N.O.	130	-
2. Vertisol (compacted)	1.50	128	98
3. Vertisol + Na^2CO^3	1.47	87	67
4. Vertisol + Alfisol	1.69	82	67

* N.O. = Observation not available

Adapted from Maheshwari (1981)

Table 2 Grain yield response (kg ha^{-1}) of cropping systems to supplemental irrigation on an Alfisol watershed, ICRISAT Center, 1981-84

			Intercropping system				
	Pearl millet			Pigeonpea			
Year	One irrigation of 40 mm	Increase due to irrigation	WAE kg mm^{-1} ha^{-1}	Two irrigations of 40 mm each	Increase due to irrigation	WAE kg mm^{-1} ha^{-1}	Combined WAE* kg $^{-1}$ mm ha^{-1}
1981-82	2710	610	15.3	1120	460	5.8	8.9
1982-83	1720	90	2.3	1180	330	4.1	3.5
1983-84	2630	510	12.8	1290	480	6.0	8.3
Average	2353	403	10.0	1197	423	5.3	6.8
	Sorghum			Pigeonpea			
1981-82	3220	400	10.0	1120	460	5.8	7.2
1982-83	3090	790	19.8	1320	610	7.6	11.7
Average	3155	595	14.9	1220	535	6.7	9.4
			Sequential cropping system				
	Pearl millet			Cowpea			
1981-82	2710	610	15.3	720	410	5.1	8.5
1982-83	1720	90	2.3	790	290	3.6	3.2
1983-84	3330	520	13.0	696	576	7.2	9.1
Average	2577	407	10.2	735	425	5.3	6.9
	Pearl millet			Tomato			
1981-82	2710	610	15.3	23200	13600	170.0	118.4
1982-83	2720	90	2.3	27300	16200	203.0	135.8
Average	2215	350	8.8	26250	14900	186.3	127.1

Adapted from Srivastava et.al. (1985)

- *One irrigation of 40 mm during rainy season and 2 irrigations of 40 mm each during post-monsson season*
- *Water application efficiency = Increase in yield due to water application / Depth of irrigation*

*Table 3 Response of sequential crops to supplemental irrigation * on a Vertisol watershed, ICRISAT Center, 1981-85*

Cropping system	Year	Yield kg ha⁻¹ Supplementally irrigated	Increase due to irrigation	Water application efficiency ** (kg ⁻¹ mm ha ⁻¹)
			Chickpea	
1. maize + chickpea sequential	1981-82	1470	310	3.9
	1982-83	1480	430	5.4
	1983-84	1830	550	6.9
	1984-85	1380	480	6.0
				Average: 5.5
			Chillies	
2. mung + chillies sequential	1981-82	1340	320	4.0
	1982-83	1490	350	4.4
	1983-84	1120	280	3.5
	1984-85	1380	350	4.4
				Average: 4.0
			Safflower	
3. maize + safflower sequential	1981-82	1160	190	2.4
	1982-83	1190	170	2.1
	1983-84	1400	150	1.9
	1984-85	1200	150	1.9
				Average: 2.0

Adapted from Srivastava et.al. (1985)

- One irrigation of 80 mm was applied at the flowering stage
- Water application efficiency = $\frac{\text{Increase in yield due to water application}}{\text{Depth of irrigation}}$

Table 4 response of grain yield (kg ha^{-1}) of early duration pigeonpea (ICPL 87) to iirigation, Alfisols, ICRISAT Center, 1984-86

Treatment	Main crop 84-85	Main crop 85-86	First ratoon 84-85	First ratoon 85-86	Second ratoon 84-85	Second ratoon 85-86	Total 84-85	Total 85-86
1. rainfed	1440	1460	660	455	175	265	2275	2180
2. full irrigation	1825	1795	895	620	325	310	3045	2775
3. 2 irrigations* (1 plant crop + 1 first ratoon)	1845	1430	900	470	330	160	3075	2060
4. 2 irrigations (both) to first ratoon)	1440	1460	995	785	355	250	2790	2495
5. 2 irrigations (one each to two ratoons)	1440	1460	940	625	285	255	2665	2340
6. rainfed (all crops harvested in one operation) **	-	-	-	-	-	-	2610	-
SE (+)	104.3	118.2	129.2	77.0	45.4	27.7	197.7	160.0
CV (%)	11	19	26	32	27	27	12	16

Adapted from Sachan and Smith (1987)

* *Number of irrigation = 6 in 1984-85 and 7 in 1985-86. Each irrigation was 50 mm*

** *Only in 1984-85*

Table 5 Effect of supplemental irrigation on crop yield

Crops	Level of irrigation (cm)	Yield (t/ha)	Yield response to irrigation (5)	Research Centre
A. Short duration rainy season crops				
Sorghum	0.6	2.51	560	Hyderabad
Maize	1	2.66	15	Jhansi
	2	4.43	40	
Finger millet	5	2.32	43	Bangalore
Soybean	8	2.05	14	Indore
B. Long duration rainy season crops				
Castor	5	1.32	31	Hyderabad
Pigeonpea	3	0.17	240	Jhansi
(Sole crop)	5	0.33	560	
Pigeonpea	2	0.04	100	Hyderabad
(as intercrop)	4	0.08	300	
Tobacco	-	1.3	58	Dantiwada
C. Postrainy season crop				
Wheat	2	1.58	35	Dehra Dun
	4	2.06	78	
	6	2.6	123	
Rape seed	1	0.35	40	Ranchi
	3	0.46	84	
	5	0.54	116	

Adapted from Vijayalakshmi (1983)

Figures 1, 2 and 2

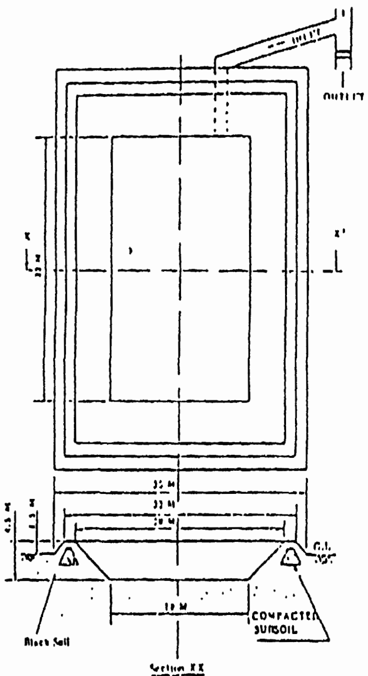

Fig 1: Details of experimental tank.

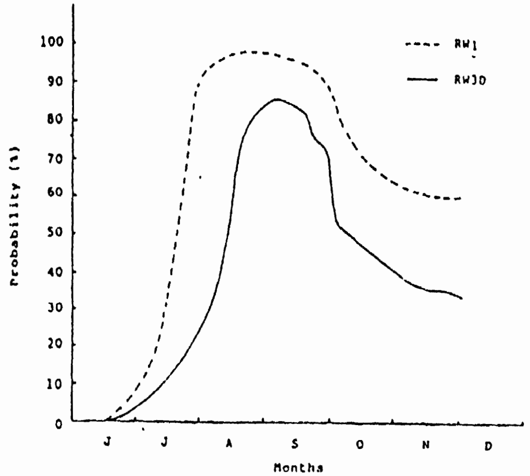

Fig. 2. Mean daily probabilities of having 40 mm water for irrigation in the tank (based on 30 years simulated data).

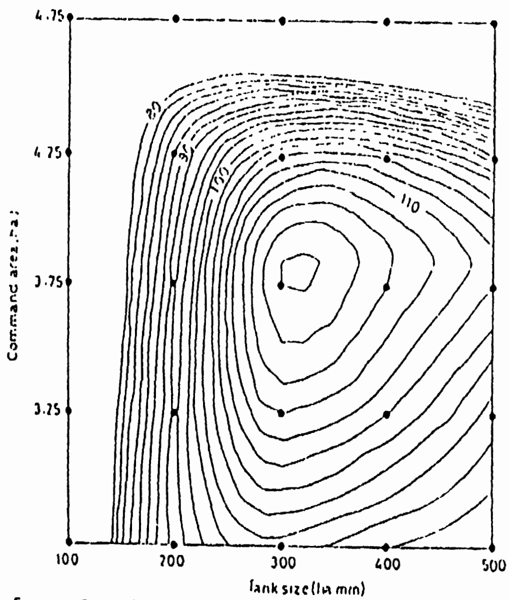

Figure 3. Economic return contours evaluated at the seepage rate of 10mm day^{-1}. Dots indicate experimental data. Figures on isoquant indicate '000 (i.e. thousand) Rupees.

(Source: Pandey, S 1986 Ph D thesis University of New England, Armidale, NSW, Australia)

In the sorghum/pigeonpea intercrop, two irrigations of 40 mm each, gave an additional gross return of Rs. 2750 ha^{-1}. The largest additional gross return from supplemental irrigation was obtained by growing tomato (7870 Rs ha^{-1}). These results indicate that on Alfisols, significant returns can be obtained from relatively small quantities of supplemental water on rainy and postrainy season crops e.g. sorghum, pearl millet, pigeonpea, cowpea and high value crops such as tomatoes and other vegetables.

Srivastava *et al.* (1985) found in a study conducted on Vertisol watersheds at ICRISAT center that average additional gross returns due to supplemental irrigation were about 630 Rs ha^{-1} for safflower, 1680 Rs ha^{-1} for chickpea, and 2110 Rs ha^{-1} for chillies. They found that the average WAE was largest for chickpea (5.5 kg/mm/ha) followed by chillies (4.0 kg mm^{-1} ha^{-1}) and safflower (2.0 kg mm^{-1} ha^{-1}; Table 3). They concluded from their experiments that irrigation was profitable for sequential crops of chickpea and chillies on Vertisols. Comparing Table 2 with Table 3, the water application efficiency was much larger on Alfisols than on Vertisols.

Rao and Sachan (1987) evaluated the water application on early maturing pigeonpea (ICPL 87) for a multiple harvest system. The results showed that where water supply is limited, irrigation should be given between the main crop and the first ratoon (Table 4). The yield increase due to two water applications ranged from 500 to 1000 kg ha^{-1}. Studies at other research stations in India have shown similar response to supplemental irrigation (Hedge *et al.* 1981, Vijayalakshmi, 1983). Crop responses to supplemental irrigation from various research centres are summarised in Table 5. Increases in crop yield of 5.6 times have been reported due to the application of supplemental irrigation.

Economic evaluation of tank irrigation systems

The economic evaluation of tank irrigation for high rainfall Vertisol areas has been carried out using a simulation model. The model consisted of several component modules for rainfall, runoff, soil moisture, yield response to irrigation, and tank- water-balance. Simulations were run for three different seepage rates, *viz.* 0, 10, 20 mm day^{-1} for a test site on a Vertisol in Central India (Madhya Pradesh). Results obtained from the simulation, shown in Fig. 3 as response surfaces approximated by quadratic polynomials, indicate that as seepage rate increases, optimal tank size increases while optimal size of the command area other factors such as runoff volume and availability of irrigable land, become constraints (Laryea *et al.* 1989). Taking the most common cropping system of the region, that is, a rainy-season fallow followed by postrainy season wheat as the base line cropping system, Pandey (1986) found that tanks are quite attractive for the soybean/wheat cropping pattern even at seepage rates as high as 20 mm d^{-1}. With the soybean/pigeonpea intercrop, the tank is profitable at seepage rates less than 10 mm d^{-1}.

The cost-benefit comparisons of various types of seepage controls (Pandey, 1986) indicated that although the benefits from seepage control are quite high, cost effective methods for controlling seepage are seemingly unavailable. Seepage control with currently available methods like sodium carbonate (0.4 kg $(m^2)^{-1}$) plus straw (0.2 kg $(m^2)^{-1}$), soil with cement (10:1) lining 15 cm thick, silt and sodium carbonate (0.4 kg m^2), or asphalt (4 l m^{-2}) were found to be viable only if the seepage rate in the uncontrolled situation was more than 20 mm/day.

CONCLUSION

Research at ICRISAT has indicated that runoff collection and utilization is feasible and can be a profitable proposition, particularly on Alfisols and to a lesser degree on Vertisols. When strategically timed during dry spells in the rainy season or used to extend the growing period into the post rainy season, supplemental irrigation markedly decreases the risks involved in rainfed agriculture and improves crop yields. There is a need to develop low cost tank sealing techniques, especially for areas having a large runoff potential.

Use of simulation models to estimate the probabilities of rainfall, runoff, moisture stress periods and expected increase in crop yields would lead to more efficient strategies for supplemental irrigation. Results from an economic evaluation using simulation model show that for the high rainfall Vertisol areas, tank irrigation of a cropping system of soybean and wheat is worthwhile even at moderate to high seepage rates. However with soybean/pigeonpea intercrop, the tank is attractive at seepage rates less than 10 mm/day.

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