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Conjunctive use of canals aquifers and managed rain waters

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Abstract

Two decision models, one for arriving at optimal systems for rainwater management and the other for allocation of additional water supplies from managed rainfall in conjunction with canal and ground water based on linear programming technique are formulated and applied to a typical alkali area under reclamation in the command of Western Yamuna Canal in Haryana. The application of rainwater management model to the command advocates the economically feasible strategies to manage rainwater. The results of rainwater management model are taken into cognizance in the later model for optimal allocation of water among competing crops. It has been shown that 80 % of rainwater could be managed economically in rice fields and in storage underground through artificial recharge. Additionally managed rainwater facilitated the extension of cultivation to fallow alkali land and increased the income of the project area by 14%.

INTRODUCTION

Water is classified into two distinct categories; Surface water and ground water. Surface water when considered in respect of irrigation, usually means water imported from the catchment areas lying upstream of the area where it actually occurred and it requires horizontal transport system (canals) to take where it is needed. Groundwater is usually developed and used in the area where it actually occurs. The replenishment of ground water takes place due to recharge from rainfall, irrigation system conveyance and field application losses. In many areas of the world, and particularly those of the Indo-Ganges basin in India, alkali soils occupy a very large area. Development of appropriate technology for reclamation and the pressure on land due to an increase in population, led to a statewide program of alkali land reclamation. This process generated demand for additional water supplies which were met by sinking large numbers shallow tube wells. The ground water withdrawal in excess of recharge over a period of time lowered the water table beyond 6-7 m, resulting in failure of shallow tube wells fitted with centrifugal pumps. Lowering of water table due to overexploitation of the ground water on one hand and the problem of surface drainage during monsoon due to poor infiltration characteristics of alkali soils and water scarcity during remaining part of the year on the other is a paradoxical situation in the semiarid tropics.

Development of appropriate rainwater management system and their integration with canals, aquifers can, to some extent, mitigate the problem of water scarcity and increase the efficiency of water resources utilization. This option of conjunctive use of rain and irrigation waters is also attractive in places where further expansion of irrigation from imported water is not feasible (Abrol et al 1988). Much emphasis was laid on conjunctive use of surface and ground waters (Buras 1963; Burt 1964; Chun et al 1964; Fowler and Valentine 1964; Dracup 1965; Eshett and Bittenger 1965; Aron et al 1969; Milligan 1969; Laxminarayan and Rajagopalan 1977; Matanga and Marino 1979; Khan 1982; Cummings and Macfarland 1984; Khepar and Chaturvedi 1987; Tyagi et al 1989; Paudyal and Gupta 1990; Subbaiah 1993; Thandaveswara et al 1993). A detailed review of these models are presented by Rao and Subbaiah (1993); Subbaiah (1999). But little efforts were made towards towards the problem of conjunctive use of managed rainwater with canals and aquifers. This study is based on a linear programming approach to arrive at optimal systems for conjunctive use of managed rain with canals and aquifers in watershed affected by soil salinity.

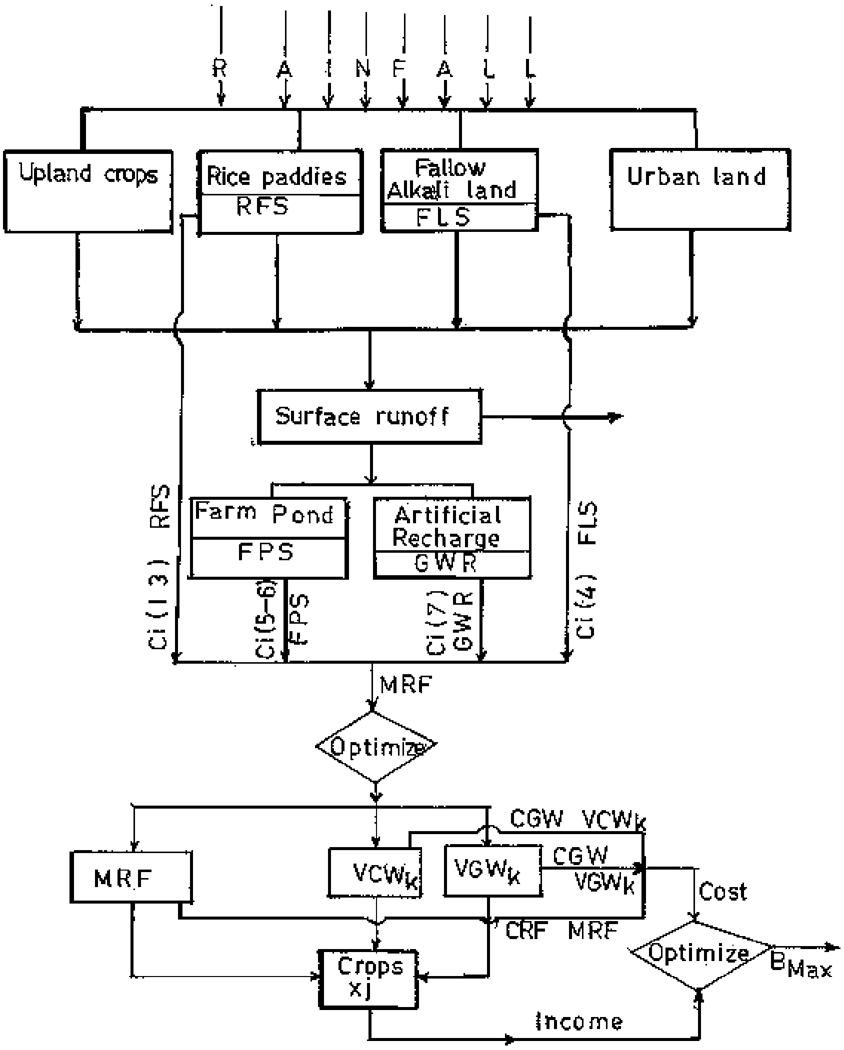

Figure 1. Schematic diagram of rainwater management and conjunctive use models.

SYSTEMS FOR RAINWATER MANAGEMENT

There could be several approaches to rainwater management and the amount of rainwater to be managed depends upon the rainfall and its distribution, the maximum expected storage depths at different return periods and several other agro-climatological factors. The difficulty in optimizing conjunctive use of irrigation and rainfall in semiarid regions lies in combining the use of limited irrigation water resources with inherently unpredictable rainfall (Stewart and Musick 1981). Narayana (1981) suggested dugout farm ponds to store rainwater and its subsequent use during dry periods in conjunction with canal and ground water. Gupta and Pandey (1979) suggested in-situ storage of rain in rice paddies. Short -term storage of rainwater could also be affected in fallow alkali land. In the present study rainfall surplus is assumed to be managed in the following rainwater subsystems: 1) storage in rice fields up to various depths (RFS); 2) Storage in fallow alkali land (RFL); 3) Storage in lined and unlined ponds (RPS); and 4) runoff diversion for artificial recharge through tubewells (GWR). The water so managed in the above systems is allocated to the crops in conjunction with canal and ground water. A schematic diagram of the model is presented in Fig.1

RAINWATER MANAGEMENT MODEL

The objective of this model is to determine the economically feasible rainwater management strategies using linear programming technique.

$$\text{Min } C = \sum_{i=1}^{m} Ci \ RWMi \tag{1}$$

where Min C = minimized cost of managing surplus rainwater; RWM_i = Volume of rainwater managed through activity; C_i = cost of managing rainwater through activity; i = A suffix for management activities. (i = 1,2,3…m)

Constraints

The above objective function (eq.1) is subjected to the following limitations:

The rainwater stored in the rice fields, fallow alkali land, and farm pond should not exceed the maximum storage capacity of the cropland (RFS), fallow land (FLS) and farm pond (FPS) respectively. Three rice field storage activities storing water up to 5 (RWM_1), 10 (RWM_2), 15 cm (RWM_3) depths are considered. One fallow alkali land storage activity (RWM_4) which stores runoff from upland cultivated area (up to 10 cm) is considered.

Two categories of farm pond, one lined (RWM_5) and the other unlined pond (RWM_6) are included.

$$\sum_{i=1}^{3} RWMi \leq RFS \tag{2}$$

$$RWM_4 \leq FLS \tag{3}$$

$$\sum_{i=5}^{6} RWMi \leq FPS \qquad (4)$$

The amount of runoff diverted towards the ground water recharge should not exceed a certain fraction of runoff available for storage.

$$RWM_7 \leq GWR \qquad (5)$$

The rainfall utilized in different rain water management activities should not exceed the maximum rainfall surplus available for management (MRF).

$$\sum_{i=1}^{7} RWM_i \leq MRF \qquad (6)$$

The energy consumed in each rainwater management activity (E_i) should not exceed the total available energy (AER).

$$\sum_{i=1}^{7} E_i\, RWM_i \leq AER \qquad (7)$$

The values of MRF and Min C are used in the conjunctive use model which allocates water to different competing crops.

CONJUNCTIVE USE MODEL

The objective of the conjunctive use model is to allocate the water to different competing crops for maximizing the benefits. Mathematically this can be expressed as:

$$\text{Max } B = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} P_{ij} - \sum_{j=1}^{n} CCW .VCW_j - \sum_{j=1}^{n} CGW.\ VGW_j - \sum_{j=1}^{n} CRF.\ MRF_j \qquad (8)$$

Where B is maximized value of the objective function; X_{ij} = Area under crop i in season j; P_{ij} = Income from crop activity i for season j; i = Suffix indicating crop index having values 1,2,3,..m; j = crop season having values 1,2,3,…n; VCW , VGW and MRF = Volume of canal water, ground water and managed surplus rainwater; CCW, CGW and CRF = Cost of canal water, ground water and managed rain water

Constraints

The above objective function (eq.8) is subjected to the following constraints:

The summation of area allocated for different crops in a particular season cannot exceed the available cultivable land

$$\sum_{i=1}^{m} \sum_{j=1}^{n} L_{ij} \; X_{ij} \leq AL_j \qquad (9)$$

where L_{ij} is land use coefficient indicating the occupancy of land under crop i during time period j. The value of $L_{ij}=1$ if the land is occupied during a particular period, otherwise it is zero; AL_j = available area of land in season, ha.

The water, labour and fertilizer requirement of various crops should be fully met during the entire crop period and must be less than the existing resources in that particular season.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} WR_{ij} \, X_{ij} \leq TWA \qquad (10)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} Ft_{ij} \, X_{ij} \leq FA_{tj} \qquad (11)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} LD_{ij} \; X_{ij} \leq LA_j \qquad (12)$$

WR_{ij} = Water requirement during jth period for the i th crop; Ft_{ij}= Fertilizer dose of t type for ith crop during jth season, kg; FA_{tj} = total fertilizer availability of type t during jth season, kg; LD_{ij} = labor days required per ha for ith crop in jth season; LA_j = Total labor available in the jth season; TWA = Total water availability.

The water diversion into the canal and the pumped ground water cannot exceed their respective capacities

$$\sum_{j=1}^{n} VCW_j \leq ACW \qquad (13)$$

$$\sum_{j=1}^{n} VGW_j \leq AGW \qquad (14)$$

where ACW and AGW is available canal and ground water, 10^3 m^3.

The yield of the crop must meet the nutritional requirements of the of the population of the study area.

Energy (calories) constraint.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} E_{ij} X_{ij} \geq EA \tag{15}$$

Protein Constraint

$$\sum_{i=1}^{m} \sum_{j=1}^{n} PR_{ij} X_{ij} \geq PRA \tag{16}$$

Iron constraint

$$\sum_{i=1}^{m} \sum_{j=1}^{n} I_{ij} X_{ij} \geq IA \tag{17}$$

Calcium constraint

$$\sum_{i=1}^{m} \sum_{j=1}^{n} Ca_{ij} X_{ij} \geq CaA \tag{18}$$

where, E_{ij} = Energy in calories per unit area from ith crop on jth season (Kcal); PR_{ij} = Protein per unit area from ith crop on jth season (Kg); I_{ij} = Iron requirement per unit area from ith crop on jth season (Kg); Ca_{ij} = calcium requirement per unit area from ith crop on jth season(Kg); EA, PRA,IA, and CaA = Total energy protein, iron and calcium requirement of the population per year (Kg).

Maximum production of certain essential cereal crops has to be ensured by putting lower limits on the area (ha) under these crops. Similarly, production of certain high value crops like sugarcane, and potatoes has to be restricted to reflect the market demands and transportation constraints by putting an upper limit on the area under these crops. These are given as follows:

Rice in alkali soil $\leq$ 75.0
Sugarcane $\geq$ 7.5
Sorghum (fodder) $\leq$ 15.0
Pigeonpea $\leq$ 40.0
Wheat in alkali Soils $\geq$ 50.0
Mustard $\leq$ 30.0
Potato $\leq$ 15.0

MODEL INPUT PARAMETERS

The main inputs to the rain water management and the conjunctive use model include: 1) in-situ storage of rain water in rice fields, 2) runoff volume, 3) maximum possible recharge volume, 4) storage in farm ponds, 5) cost of rainwater management activities, 6) energy requirement, 7) cost of surface and ground waters and 8) income for different crop production activities. These inputs were determined for a typical alkali catchment of 220 ha in the command of Saidpura-dabri watercourse near Karnal, which had about 30% of its land in alkali category. The rainfall distribution is such that 70% of the 720 mm of rainfall occurs during the three months of July to September. The analysis of rainfall storm values of different duration's of Karnal shows that in a five year return period, the maximum storm depths for 1,2,3, consecutive days duration's were 152, 201 and 219 mm respectively (Tyagi et al 1989; Subbaiah 1991).

Storage in Rice Fields

The volume of water that can be stored in rice fields is a function of the maximum permissible storage depth, area under the rice crop and distribution of the rainfall Gupta and Pandey (1979) and Narayana (1981) mentioned that 15 cm of water could be conveniently stored in rice fields without reduction in the crop yield. The storing of rainwater in the field involves the construction of bunds of different sizes depending upon the level to which rainwater is stored. The cost of storage includes the cost of the earthwork and the land lost to production, which increases with the height of storage. Three levels of storage mainly 5 cm (RWM1); 10 cm (RWM2) and 15 cm (RWM3) were considered. Based on daily water balance and for a 5 year return period which is generally used in agricultural planning the volumes that could be stored at these depths were 306, 390, and 415 X 10^3 m^3 respectively for an area of 75 ha which falls under the alkali category. The cost of storage which comprised of the cost of the earth work and the land lost in bunds was estimated to be Rs. 56, 66 and 85 per 10^3 m^3 of water in the case of 5,10 and 15 cm storage levels.

Storage in Fallow Alkali Land

About 15 ha of fallow alkali land was available for storing rainwater. This water could be diverted to cropland with in a period of 2 to 4 days. A daily pan evaporation of 3 mm/day and a deep percolation loss of 5 mm/day (Subbaiah 1987) the storable volume of 5 year return period was 25.5 X10^3 m^3.

Runoff Volume

The USDA-SCS method was employed to compute the direct runoff. The weighted curve number for the area was estimated to be 71. At 5-year return period the runoff from the catchment was worked out to be 66.7 mm

Storage in Farm Ponds

Runoff produced from upland crops, urbanized lands and uncultivated alkali land could either be stored in farm ponds or recharged through wells or allowed to flow out of the area. Farm ponds occupy land and the water stored in ponds is subject to loss through evaporation and seepage. Therefore, only a limited amount of water can be made available through farm ponds. As the water is being continuously removed from the pond during the dry spell, the design depth was taken only 2/3 of the runoff estimated above i.e. 44.5 cm. The total storable runoff yield was 98 X 10^3 m^3. Assuming that farm ponds were uniformly distributed in the catchment each pond was designed to store 9.8 X 10^3 m^3. Two types of farm ponds i.e. brick lined (RWM_5) and unlined pond (RWM_6) were considered in this study. After accounting for evaporation and seepage losses the effective storage was worked out to be 7.74 X 10 ^{3} m^3 and 4.9 X 10 ^{3} m^3 for lined and unlined ponds respectively. The costs of storage for the unlined and lined ponds were 914 and 3752 per 10 ^{3} m^3**.**

Ground Water Recharge

Rainwater management activities including storage in rice field's fallow land and farm ponds, lead to increased recharge. Based on application efficiency of 50% (Tyagi 1980) for rice grown in alkali soil and a recharge fraction of 0.8, the recharge from rice fields for 5, 10, and 15 cm storage for the entire growing season was estimated to be 1.22, 1.56 and 1.66 X 10 ^{3} m^3 /ha respectively. The recharge volumes from lined and unlined ponds were estimated to be 10 and 32.5 X 10 ^{3} m^3 (Subbaiah 1991)

Artificial Ground water Recharge Through well points

Recharge from the rice fields and from ponds is a byproduct of rainwater storage, their primary aim being a direct water supply to crops, artificial recharge through the wells has been considered as a separate activity. A recharge well is one, which admits water from the surface to an underground formation. The flow to a recharge well is the reverse of a pumping well. Based on Dupuit's assumptions, Todd (1959) derived following equation for the rate of recharge from a well penetrating an unconfined aquifer

$$Q_r = k (h_w^2 - h_o^2)/ [\ln (r_o / r_w) \qquad (19)$$

Where Q_r = Recharge rate; k = hydraulic conductivity of the aquifer; r_o = radius of influence **;**

r_w = radius of the well; h_w = hydraulic head in the recharge well; and h_o = hydraulic head at radius of influence. Studies indicated (Subbaiah 1987) it was possible to recharge the well at a rate of 7.5lps. In the study area, well fields for recharge could be constructed along the drains and in the depressional areas where water was available for recharge throughout rainy season. Based on the aquifer properties, topographic situation and time distribution of the rainfall the total recharge capacity was estimated to be 73.4 X 10 ^{3} m^3.

Total Available Energy

Ground water has to be pumped before it becomes available for use by the crops. There is an acute shortage of the energy in the study area and the electricity for running the tube wells is available for only 8 to 10 hours. For an electricity supply of 8 hours over a period of 3 months and considering the norms for sanctioning the electricity connection for tube wells, the maximum limit of total available energy (AER) was 30000 kWh.

EMPIRICAL RESULTS

The rainwater management model was used to determine cost activities for rainwater levels of (1) manageable rainfall; (2) cost coefficients of farm ponds and fallow land storage, and (3) energy availability. The conjunctive use model was used to allocate water from canals, groundwater and managed rainwater, to different crops in an optimal manner.

Manageable Rainfall Levels

Manageable rainfall represents the volume of rainfall available for storage in different rainwater management sub-systems. The maximum value of available runoff at a 5-year return period was 600×10^3 m^3 . The results (Table 1) revealed that at 500×10^3 m^3 level of manageable rainfall, which seems reasonable to achieve, 61.2 % was stored in rice fields at 5 cm storage (RWM_1), 21.8% in rice fields at 10 cm storage (RWM_2) and only 2.4 % in fallow land (RWM_4). The remaining 14.6% was stored in groundwater storage through artificial recharge by inverted tube wells (RWM_7).

Table 1. Optimal Rainwater Management Activities at Different Rainfall Utilization Levels.

Rainfall Man-agement level $\times10^3$ m^3	Rainwater management activity level 10^3 m^3						
	RWM_1	RWM_2	RWM_3	RWM_4	RWM_5	RWM_6	RWM_7
200	200.0		-		-	-	
300	300.0		-		-	-	
400	306.0	94.0	-		-	-	
450	306.0	109.2			-	-	34.8
500	306.0	109.2		11.4	-	-	73.4
550	306.0	152.6		18.0	-		73.4
600	306.0	195.0		22.0		3.60	73.4

Storage in farm ponds, weather lined or unlined (RWM_5 , RWM_6) , did not enter the optimum solution due to the high unit cost of storage. Rainwater in rice fields was the most cost-effective alternative and entered the optimal solution at the maximum prescribed level. Compared to storage in farm ponds, artificial recharge through tube wells appeared to be a preferable alternative. A change in the level of manageable rainfall from 200-600×10^3 m^3 indicated that, at low levels of manageable resource (up to 400×10^3 m^3), all the water was stored in rice fields only. If the manageable resource is increased beyond 400×10^3 $m^{3,}$ other alternatives, such as fallow land and artificial recharge, entered the optimal plan. Storage in farm ponds did not find a place, even at maximum level of manageable rainfall. Results from the cost minimization model indicated that even if the cost of farm-pond storage were 50% of the estimated cost; it would not be cost-effective to store water in them (Table 1)

Effect of Energy Supply

Energy is needed for the activities that require the pumping of water from pond or groundwater. Of the seven activities considered in the model, rainwater storage in rice fields and fallow land had zero energy requirements. Activities RWM_2 remained unchanged with change in energy availability (Table 2.). However, at very low level of energy supply (20000 kWh), part of RWM_7 (groundwater recharge through tubewell) got submitted by RWM_4 (fallow land storage). It is reasonable to conclude that artificial groundwater recharge and subsequent pumping would find favor only where sufficient energy was available for pumping.

Table 2. Optimal Rainwater Management Activities at Different Energy Availability Levels.

Energy level (kWh)	Rainwater management activity level 10^3 m^3							Cost (Rs× 10^3)
	RWM_1	RWM_2	RWM_3	RWM_4	RWM_5	RWM_6	RWM_7	
20000	306.0	145.2	-	22.5	-	-	26.3	35.04
22500	306.0	127.2	-	16.9	-	-	50.3	33.67
25000	306.0	109.2	-	11.4	-	-	73.4	34.35
27250	306.0	109.2	-	11.4	-	-	73.4	34.35
30000	306.0	109.2	-	11.4	-	-	73.4	34.35
35000	306.0	109.2	-	11.4	-	-	73.4	34.35

Table 3. Optimal Cropping Pattern Without and With Rainwater Management Activities.

Crop	Without rainwater management			With rainwater management			Remarks
	Area (ha)	%of total area	Income ((Rs×10^3)	Area (ha)	%of total area	Income (Rs×10^3)	
Summer							Sugar-Cane is annual crop Increase in income Rs.85.61×10^3
Rice	50.0	33.3	125.0	75.0	50.0	187.5	
Sugarcane	7.5	5.0	21.7	30.0	20.0	86.7	
Mize	7.2	4.8	7.8	-	-	-	
Sorghum	15.0	10.0	37.8	15.0	10.0	37.8	
Pigeon Pea[a]	-	26.6	66.2	30.0	20.0	66.2	
Pigeon Pea	40.0	20.3	-	-	-	-	
Fallow Land	30.3	-	-	-	-	-	
Total	150.0	100.0	258.5	150.0	100.0	387.2	
Winter							
Wheat	60.0	40.0	76.0	60.0	40.0	76.0	
Berseem	15.0	10.0	43.5	15.0	10.0	43.5	
Mustard	30.0	20.0	71.1	30.0	20.0	71.1	
Potato	15.0	10.0	48.8	45.0	10.0	48.8	
Fallow Land	22.5	20.0	-	-	-	-	
Total	142.5	100.0	239.40	150.0	80.0	239.40	
Water resource utilized							
1.Canal	375×10^3 m^3				375×10^3 m^3		
2.Ground-water	500×10^3 m^3				397×10^3 m^3		
3.Managed rain	-				450×10^3 m^3		
4.Total	875×10^3 m^3				1222×10^3 m^3		

[a] Irrigated pegion pea.

Cropping Pattern

The optimal cropping patterns under the two water supply conditions with and without conjunctive use of rain and irrigation waters) are discussed elsewhere (Subbaiah et al 1992). The total net income under the situation of non-conjunctive use was Rs.426.55×10^3 with a total water use of 875×10^3 m^3. Optimal rainwater management made available an additional 450×10^3 m^3 of water for meeting crop water requirements. This permitted a greater area under irrigated crops and also made it possible to grow high water requiring crops that had higher profitability. (Table 3). Rice and sugarcane were the major beneficiaries as the area under rice increased from 33 to 50%, and under sugarcane from 5 to 20%. With the result, the total net income increased from Rs. 26.55×10^3 to Rs. 512.51×10^3. It represented an increase of 16% over the income without rainwater management. The effect of different levels of rainwater management activities on the net income was investigated through parametric programming. It was interesting to note that at low level of managed rainwater, the income increased rapidly, attaining a maximum of Rs. 850×10^3 at 450×10^3 of water use and then came down to Rs.830×10^3 at 500×10^3 m^3 . The total net income further decreased to about Rs.750×10^3 at a managed rainwater level of 600×10^3 m^3. It implied that storage of rainwater beyond 500×10^3 m^3, through less cost-effective means like farm pond storage was not profitable.

SUMMARY AND CONCLUSIONS

The lowering of water table due to over exploitation of ground water on one hand and wastage of good quality of rainwater, which creates flood problems on the other, is a paradoxical situation. Development of appropriate rainwater management system and their integration with canals and aquifers can to some extent mitigate the problem of water scarcity and increase the efficiency of water resources utilization. The study revealed that it is profitable to store only 80% of the runoff through suggested rainwater management system. Utilization of managed rainwater in conjunction with irrigation waters increased the income of the project area.

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