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Optimal irrigation planning model for an existing storage based irrigation system in India

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Abstract A weekly irrigation planning LP model is formulated for determining the optimal cropping pattern and reservoir water allocation for an existing storage based irrigation system in India. Objective of the model is maximization of net annual benefit from the project. In an irrigation planning of a storage based irrigation system, initial storage of the reservoir at the beginning of the reservoir operation, expected inflows into the reservoir during each intraseasonal period, capacity of channels, crop calendar and yield response to water deficit in each growth stage of crop play a vital role in deciding acreage and water allocation to each crop. The planning model takes into account yield response to water deficit in each intraseasonal period of the crop, expected weekly inflows entering into the reservoir, storage continuity of reservoir, land and water availability, equity of water allocation among sub areas and proportionate downstream river release. One year comprising of 52 weeks is considered as planning horizon. To account for uncertainty in water resources availability, the model is solved for four levels of reliability of weekly inflows entering into the reservoir (90%, 85%, 80% and 75%). Alternative optimal cropping patterns and weekly releases to crops grown in each sub area under each main canal are obtained for various states of initial storage at the beginning of reservoir operation and for various levels of weekly inflows into the reservoir. Results reveal the importance of initial state of reservoir storage for feasible solution and shows the impact on cropping pattern with the change in initial storage of reservoir for different levels of reliability of weekly inflows.

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Keywords Allocation of resources · Irrigation planning · Linear programming · Optimization model

Introduction

Water plays a critical role in the agricultural development. Recognizing the importance of irrigation, huge investments are made expanding the irrigated area by building irrigation projects. With the growing demand for food due to increase in population, it is necessary to increase the food production by bringing more area under cultivation or by increasing the food production per unit area with the available limited resources. Due to the growing competition for the limited available water in different sectors, it is high time to review and improve the efficient use of irrigation water of existing projects by implementing optimal irrigation planning and water management policies rather than investing on new projects.

When irrigation water is insufficient, appropriate scheduling can increase crop yields. A deficit occurring in certain stage of crop growth may cause a greater reduction in yield than the same amount of deficit occurring in some other growth stages. As the crop water response to water deficit at different periods is not uniform, it is necessary to distribute deficits among intraseasonal periods optimally for a crop. Several factors are to be considered in irrigation planning, particularly when several crops are grown in the same command area in more than one season in a year. Two distinct decisions to be made are how much water and land should be allocated to each crop. The strategy of allocation of land and irrigation for intraseasonal periods of a crop is to maximize net income from the project.

Optimization models have been used extensively in water resources systems analysis and planning (Loucks et al. 1981). The problem of irrigation scheduling in case of limited seasonal water supply has been studied extensively for single crop situation (Bras and Cordova 1981; Rao et al. 1988). Number of researchers addressed the problem of allocation of a limited water supply for irrigation in multi-crop environment (Rao et al. 1990; Sunantara and Ramirez 1997; Paul et al. 2000; Umamahesh and Sudarsan Raju 2002; Teixeira and Marino 2002). Many researchers used Linear Programming models as an effective tool for optimal cropping pattern and water allocations as they can handle large number of constraints (Khepar and Chaturvedi 1982; Chavez-Morales et al. 1987; Mayya and Prasad 1989; Onta et al. 1995; Panda et al. 1996; Mainuddin et al. 1997; Singh et al. 2001; Sethi et al. 2002). In an irrigation planning of a storage based irrigation project, initial storage of the reservoir at the beginning of the reservoir operation, expected inflows into the reservoir during each intraseasonal period, capacity of channels, crop calendar and yield response to water deficit in each growth stage of crop play a vital role in deciding acreage and water allocation to each crop. In the present study, an LP weekly planning model is formulated maximizing the annual net benefit from the project to obtain optimal cropping pattern and weekly releases to crops grown in each sub area under each main canal. The planning model takes into account yield response to water deficit in each intraseasonal period of the crop, expected weekly inflows entering into the reservoir, storage continuity of reservoir, land and water availability, equity of water allocation among sub areas and proportionate downstream river release. One year comprising of 52 weeks is considered as planning horizon. The model developed is demonstrated by applying to Nagarjuna Sagar Project (NSP) in the state of Andhra Pradesh in India.

The study area

The Nagarjuna Sagar Project (NSP) project is taken up for the present study and is located on the river Krishna in the state of Andhra Pradesh in India (Fig. 1). Two canals take off from the reservoir on either flanks, right main canal and left main canal. The length of right main canal is 203 km and that of left main canal is 295 km. The maximum area available for planting is 450,000 ha for sub area-1 under right canal and 386,812 ha for sub area-2 under left canal. The designed head discharge of each main canal is 312 m^3/s. The reservoir is located at latitude 16°–34′ N and longitude 79°–19′ E with a live storage capacity of 5,733 million cubic meters (MCM). The command area under NSP project falls under semi-arid tropical region with an average annual rainfall of 938 mm, two thirds of which occurs during the period June to October. However, the area experiences prolonged dry spells during the same period, which are critical for the survival of crops. As per the Krishna Water Dispute Tribunal (KWDT) award, water allocated to N S Project is 7,958 MCM in which 3,738 MCM is allocated to left canal, 3,738 MCM for right canal and 482 MCM

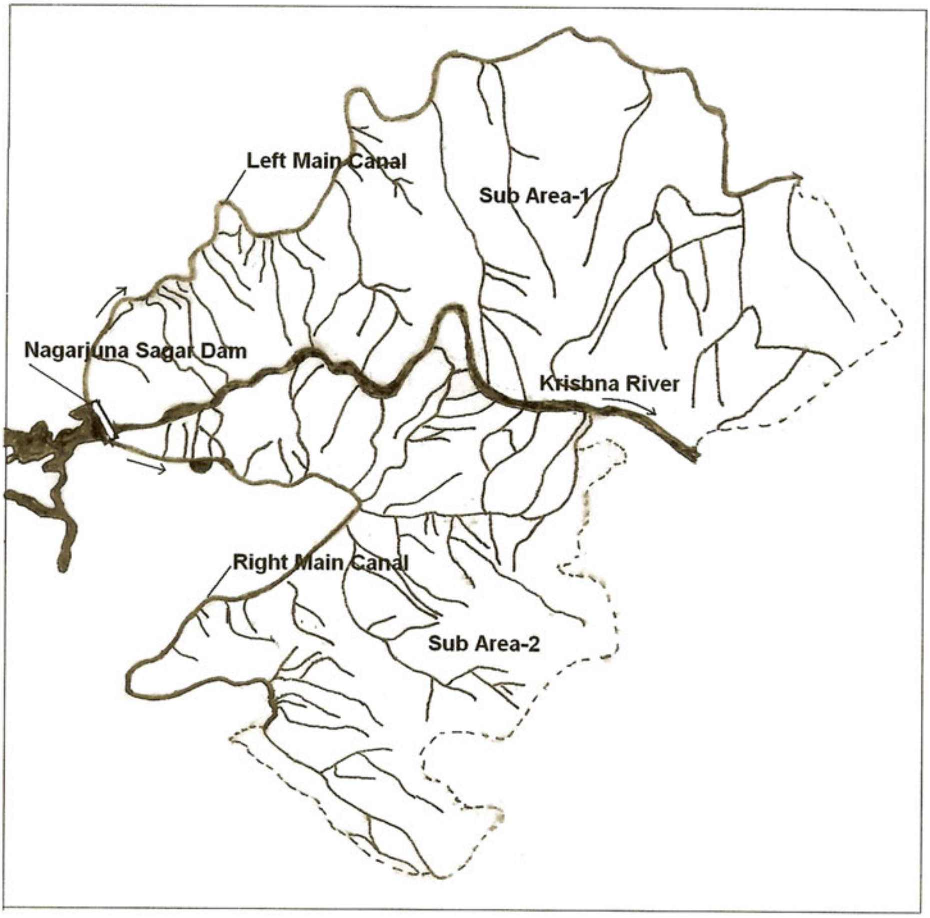

Fig. 1 Schematic representation of Nagarjuna Sagar Project Layout

towards evaporation losses in the N S Reservoir. 2,266 MCM of water is to be released to the downstream river to augment the irrigation demands of Krishna delta ayacut considering the 75% dependable flows entering into the reservoir. The soils in the area are dark grey-brown to black deep clay with fine to very fine texture. The study area is characterized by two distinct seasons Kharif (rainy) and Rabi (dry). The Kharif season is from July through October and the Rabi season from November through February. Major crops that are being grown are rice, groundnut, sorghum and grams in Kharif season, groundnut, sorghum, grams in Rabi season and chilli, cotton as two seasonal crops. In the initial years when entire command area is not developed, farmers are encouraged to cultivate crops of their choice in the areas where irrigation water could reach. As a result farmers took to cultivation of rice in most of the area in Kharif season, as it is the staple food of local people. The command area witnessed severe shortage of water due to continuous droughts in recent years in addition to the reduction in inflows into the reservoir of the project due to the development of upstream irrigation projects on Krishna River. This necessitates the adoption of optimal irrigation planning.

Model formulation

The irrigation planning model is formulated to identify the acreage of each crop in multicrop environment and weekly releases of reservoir maximizing the net economic returns from the project. The decisions to be made depends on availability of land and water resources, reliability of water supply, suitability of soil to crops, storage capacity of reservoir, channel conveyance capacities and socio-economic factors. Depending upon the availability of resources, two strategies can be applied i) Full irrigation: satisfying the full irrigation requirements of crops when sufficient water supply is available. ii) Deficit irrigation: deliberately under irrigating the crops bringing more area under cultivation with limited water supply. If water is the limiting resource, it is necessary to optimally distribute the amount of water through different intraseasonal periods considering the yield response to water deficit with the limited supply. In this way, optimized procedures for land and water allocations are ensured to maximize annual net benefit of an irrigation scheme. The model is developed for determining optimal acreage and weekly irrigation releases from the reservoir for each crop grown under each main canal, downstream river release and spill over the reservoir. The problem is solved by a linear programming model maximizing the net benefit from the project subjected to constraints of land and water availability, reservoir storage continuity, release-demand, equity of release among sub areas, channel capacity etc., leading to an optimal solution.

Development of objective function

The differential nature of crop yield response to different levels of soil moisture contents available to it gives rise to the concept of water production functions of crops. The additive model of dated water production function is considered in the present study (Doorenbos and Kassam 1979).

$$\frac{\mathrm{Y}_{i,c}}{\mathrm{YM}_{i,c}} = 1 - \sum_{t=1}^{\mathrm{NT}_{i,c}} \mathrm{KY}_t \left(1 - \frac{\mathrm{ETA}_t}{\mathrm{ETM}_t}\right) \tag{1}$$

where $\mathrm{Y}_{i,c}$ is the actual yield with the available water, $\mathrm{YM}_{i,c}$ is the maximum yield that can be obtained when there is no limitation of water. ETA_t, ETM_t and KY_t are the actual evapotranspiration, potential evapotranspiration and the yield response factor of intraseasonal period ‘t’ of the total crop period. $NT_{i,c}$ is total number of intraseasonal periods of crop. One week is chosen as intraseasonal period and the duration of the physiological crop growth stage is adjusted as integral multiple of a week. Actual evapotranspriration ETA (mm) is estimated as the sum of net irrigation applied and effective rainfall.

$$ETA_{i,c,t} = \frac{R_{i,c,t}EF_{i,c}}{A_{i,c}} \times 1.0e05 + RE_t \tag{2}$$

where $R_{i,c,t}$ is the release to crop c of sub area ‘i’ in time period ‘t’ in million cubic meters (MCM) and $A_{i,,c}$ is the area of crop ‘c’ of subarea ‘i’ in hectares, $EF_{i,c}$ is the efficiency of irrigation of crop ‘c’ of subarea ‘i’ and RE_t is effective rainfall (mm) in time period ‘t’.

Weekly potential evapotranspiration of crop is estimated as

$$ETM_{i,c,t} = KC_{i,c,t}ETO_t \tag{3}$$

where $KC_{i,c,t}$ is crop coefficient of crop ‘c’ of sub area ‘i’ in time period ‘t’ and ETO_t is the reference evapotranspiration in time period ‘t’. The net benefit for each crop can be estimated as

$$NB_{i,c} = PC_{i,c}Y_{i,c}A_{i,c} - CC_{i,c}A_{i,c} \tag{4}$$

where $PC_{i,c}$ is the market price per unit yield (Indian rupees), $Y_{i,c}$ is the yield per unit area (kg/hectare), $CC_{i,c}$ is the cost of cultivation per unit area (rupees/hectare) and $A_{i,c}$ is area of crop ‘c’ of sub area ‘i’ (hectares). Total annual net benefit from all crops grown under the two main canals of the project is

$$TNB = \sum_{i=1}^{2}\sum_{c=1}^{NC_i} NB_{i,c} \tag{5}$$

Combining the Eqs. 1, 2, 3, 4 and 5, objective function for total net benefit can be obtained as

$$TNB = \sum_{i=1}^{2}\sum_{c=1}^{NC_i}\left(\alpha_{i,c}A_{i,c} + \sum_{t=1}^{NT_{i,c}}\beta_{i,c,t}\,R_{i,c,t}\right) \tag{6}$$

where

$$\alpha_{i,c} = PC_{i,c}YM_{i,c}\left(1 - \sum_{t=1}^{NT_{i,c}}\left\{KY_{i,c,t} + \frac{KY_{i,c,t}RE_t}{ETM_{i,c,t}}\right\}\right) - CC_{i,c} \tag{7}$$

and

$$\beta_{i,c,t} = PC_{i,c}YM_{i,c}EF_{i,c}\left(\frac{KY_{i,c}}{ETM_{i,c,t}}\right)10^5 \tag{8}$$

To ensure sufficient carry over year storage and to minimize the reservoir spill SP (MCM), a penalty term is added to the simple objective function (6) as follows:

Maximize

$$\sum_{i=1}^{2}\sum_{c=1}^{NC_{i,}}\left(\alpha_{i,c}A_{i,c}+\sum_{t=1}^{NT_{i,c}}\beta_{i,c,t}R_{i,c,t}\right)-M\sum_{t=1}^{52}SP_t \tag{9}$$

where M is sufficiently large number to minimize the spill SP_t

The modified objective function (9) is maximized by linear programming subjected to the following linear constraints.

Land resources availability

(i) Maximum total cropped area grown under each main canal 'i' in any season cannot be greater than total available land TA_i

$$\sum_{c=1}^{NC_i} CI_{i,c,s}A_{i,c} \le TA_i \quad \forall i, s \tag{10}$$

where $CI_{i,c,s}$ is the index of crop 'c' in season 's' and is equal to 1 if the crop is grown in season 's' and is zero otherwise.

(ii) Maximum and minimum allowable crop area

Considering the economical and social factors such as maintaining market price, economic status of the farmers, food habits of the people etc., maximum and minimum bounds on crop area is to be imposed. A certain minimum area is to be occupied by food crops like rice to cater the local demands even though the benefit from those crops may not be attractive when compared to commercial crops like cotton & Chilli. At the same time, if more area is occupied by the commercial crops and production is more than market demand, market price comes down. Therefore maximum and minimum bounds are to be imposed considering the local needs and market price.

For maximum area

$$A_{i,c} \le AMAX_{i,c} \quad \forall i, c \tag{11}$$

For minimum area

$$A_{i,c} \ge AMIN_{i,c} \quad \forall i, c \tag{12}$$

Water availability constraints

(i) Total annual allocation of water to each sub area should not exceed the maximum water permitted for utilization TR_i

$$\sum_{c=1}^{NC_i}\sum_{t=1}^{52} CI_{i,c,t}R_{i,c,t} \le TR_i \quad \forall i \tag{13}$$

where $CI_{i,c,t} = 1$ if the crop 'c' of sub area 'i' is present in the field in time period 't' and is equal to zero if it is not present.

(ii) Total annual downstream river release should not exceed the maximum water permitted to the downstream projects TRR

$$\sum_{t=1}^{52} RR_t \leq TRR \tag{14}$$

Equity in water allocation

(i) Total annual water allocated to each sub areas under left and right canals, should be equal as per the Krishna Water Dispute Tribunal (KWDT) award.

$$\sum_{c=1}^{NC_1}\sum_{t=1}^{52} CI_{1,c,t}R_{1,c,t} - \sum_{c=1}^{NC_2}\sum_{t=1}^{52} CI_{2,c,t}R_{2,c,t} = 0 \tag{15}$$

(ii) To satisfy the irrigation demands of downstream irrigation projects, downstream river releases must be greater than or equal to a fraction of the total release allocated to project sub areas in each time period.

$$RR_t - k\sum_{i=1}^{2}\sum_{c=1}^{NC_i} CI_{i,c,t}R_{i,c,t} \geq 0 \quad \forall t \tag{16}$$

where k is the fraction of the total release allocated to right and left main canals of the project.

Maximum and minimum bounds on water allocation to each crop

(i) Maximum release to each crop is restiricted by its irrigation requirement $IRR_{i,c,t}$ (mm) in any time period.

$$R_{i,c,t} - \frac{IRR_{i,c,t}}{EF_{i,c}x1.0e05}A_{i,c} \leq 0 \quad \forall i, c, t \tag{17}$$

(ii) Minimum limit on release to each crop in any time period is restricted to certain fraction ($p_{i,c}$) of the irrigation requirement as yields decrease drastically if the level of irrigation falls below it.

$$R_{i,c,t} - \frac{p_{i,c}xIRR_{i,c,t}}{EF_{i,c}x1.0e05}A_{i,c} \geq 0 \quad \forall i, c, t \tag{18}$$

Canal carrying capacity

The total water diverted into the main canal of each sub area in any time period ‘t’ should be less than or equal to its designed carrying capacity during the same time period $QMAX_i$

$$\sum_{c=1}^{NC_i} R_{i,c,t} \leq QMAX_i \quad \forall i, t \tag{19}$$

Reservoir storage continuity

Water balance of reservoir is governed by reservoir storage continuity equation.

$$S_{t+1} = S_t + I_t - \sum_{i=1}^{2}\sum_{c=1}^{NC_i} R_{i,c,t} - RR_t - SP_t - EVP_t \quad \forall t \tag{20}$$

where S_t is live storage of the reservoir at the beginning of the time period 't', I_t, SP_t and EVP_t are the inflow, spill and evaporation of the reservoir during time period 't'. Approximating the evaporation loss following Loucks et al. (1981), the equation is modified as

$$(1 + a_t)S_{t+1} - (1 - a_t)S_t + \sum_{i=1}^{2}\sum_{c=1}^{NC_i} R_{i,c,t} + RR_t + SP_t = I_t - A_0 e_t \quad \forall t \tag{21}$$

where

$$a_t = \frac{A_a e_t}{2} \quad \forall t \tag{22}$$

and A_0 is the water spread area corresponding to dead storage volume, A_a is the water spread area per unit live storage volume above the dead storage level and e_t is the evaporation rate in period 't'.

Reservoir storage capacity

The live storage of the reservoir in any time period S_t should not exceed its storage capacity S_{max}.

$$S_t \leq S_{max} \quad \forall t \tag{23}$$

Carry over year storage

To ensure that there is ample water for next irrigation season, the carry over year storage (SCY) is specified to be greater than or equal to 1000 MCM and should be less than maximum storage capacity of the reservoir.

$$SCY \geq 1000 \tag{24}$$

$$SCY \leq S_{max} \tag{25}$$

Non-negativity

All the decision variables must be greater than or equal to zero.

$$A_{i,c} \geq 0 \quad \forall i, c \tag{26}$$

$$R_{i,c,t} \geq 0 \quad \forall i, c, t \tag{27}$$

$$RR_t \geq 0 \quad \forall t \tag{28}$$

$$SP_t \geq 0 \quad \forall t \tag{29}$$

Estimation of model inputs

Irrigation requirement of crops

The crop water requirement is computed following the guide lines given by Allen et al. (1998). A reference evapotranspiration ETO is first calculated from the weather data by the Penman-Monteith method. The growing period is divided into five general growth stages viz., initial, crop development, flowering, grain formation and ripening stage. Duration of crop growth stages are adjusted to integral multiple of weeks. Crop coefficients during the initial period (KC_{ini}), middle period (flowering and grain formation, KC_{mid}) and at the end of the ripening period (KC_{end}) are estimated. Crop coefficient curves are developed for all crops considered in the present study. Weekly potential evapotranspiration for each crop is obtained using the KC values from the curves as

$$ETM_{c,t} = KC_{c,t}ETO_t \tag{30}$$

Net irrigation requirement (NIR) is estimated as

$$NIR_{c,t} = ETM_{c,t} - RE_t \tag{31}$$

where RE_t is the effective rainfall in time period 't'.

Weekly inflows into reservoir

From the historical record of daily inflows entering into the reservoir, weekly flows are determined. The obtained weekly flows are transformed by a mathematical function, such that the transformed series is normally distributed. This implies that the transformation function reduces the skewness to zero. Box-Cox transformation (Box and Cox 1964) is adopted in the present study.

$$Y = \frac{X^{\lambda} - 1}{\lambda} \text{ if } \lambda \neq 0 \tag{32}$$

$$Y = \ln X \text{ if } \lambda = 0 \tag{33}$$

in which X and Y are the observed and transformed data respectively. The value of λ is arrived at by trial as that value which reduces the skewness of the transformed series to zero. Testing for goodness of fit is done through the chi-squared test and test is accepted the developed distribution at 10% significance level. Expected weekly inflows into the reservoir at 90%, 85%, 80% and 75% probability of exceedence (PE) are estimated from the distribution fitted.

Assumptions

The following assumptions are made to reduce the complexity of the problem.

(i) Soil moisture dynamics in the root zone is neglected and total amount of water applied is assumed to be readily available to the plant and equal to the actual evapotranspiration.
(ii) Irrigation requirements are treated as deterministic and assumed to be uniform over the entire command area.
(iii) Market price of unit quantity of crop produced is assumed to be fixed.

A total of ten crops rice, delayed rice, groundnut, sorghum, grams in Kharif season and groundnut, sorghum and grams in Rabi season including two seasonal crops chilli and cotton are considered in the present study for each sub area commanded by right and left main canals. Rice is transplanted as early rice (Rice-1) and delayed rice (Rice-2) with a lag of 2 weeks to reduce the peak demands. Data to compute ETo is obtained from a nearby weather station, Rentachintala (30 years of data is available). Monthly mean daily ETo in mm/day is computed for the observed meteorological data and is shown in Table 1. Basic crop data of all crops considered is obtained from the state department of irrigation and is presented in Table 2. Estimated KC values and net seasonal irrigation requirement of crops are presented in Table 3.

While applying optimal allocations of water and land, upper and lower bounds on area and irrigation are imposed considering the local requirements and food habits of the people (Table 4.). As rice is the principal crop grown, a minimum area of 100,000 ha under each sub area is fixed to satisfy the local food requirements. Rice is irrigated by flooding method

Table 1 Meteorological data and estimated reference evapotranspiration ETo

Month	Daily temperature (°C)		Daily relative humidity (%)		Relative sunshine duration	Monthly rainfall (mm)	No. of rainy days	Wind speed (kmph)	ETo (mm/day)
	Max.	Min.	Max.	Min.					
January	31.2	17.3	71	33	0.685	0.4	0.1	5.0	4.00
February	34.1	19.9	67	31	0.690	9.3	0.8	6.5	4.72
March	37.5	23.0	63	28	0.725	6.1	0.4	8.1	5.62
April	39.6	26.1	61	28	0.610	9.6	1.4	8.8	6.16
May	41.5	28.6	55	31	0.500	40.8	2.9	10.4	6.44
June	37.8	27.3	61	43	0.240	86.2	5.9	14.5	5.67
July	34.1	25.3	70	54	0.150	115.3	8.9	13.3	4.92
August	33.9	25.6	70	55	0.188	114.6	7.8	11.8	4.64
September	33.4	24.8	74	61	0.248	146.1	8.1	7.9	4.34
October	32.9	23.2	76	57	0.405	123.8	6.9	4.8	4.11
November	30.8	19.6	74	50	0.530	41.1	2.8	4.0	3.81
December	29.9	16.8	73	41	0.655	13.3	0.7	3.8	3.70

Station: Rentachintala Latitude: 16° 33′ Longitude: 79° 33′ Height above MSL: 106.0

Table 2 Basic crop data

Crop (Season)	Date of sowing (Standard week)	Duration of growth stages in weeks and yield response factors KY				
		Initial	Crop development	Flowering	Grain formation	Ripening
Rice(K)	1 July (27)	2, 1.10	5, 1.10	3, 2.40	3, 2.40	3, 0.33
Groundnut(K)	1 July (27)	3, 0.20	3, 0.20	2, 0.80	4, 0.60	3, 0.20
Sorghum(K)	16 July (29)	3, 0.20	3, 0.20	2, 0.55	4, 0.45	3, 0.20
Grams(K)	16 July (29)	3, 0.05	4, 0.05	2, 0.40	4, 0.35	2, 0.20
Cotton	16 July (29)	4, 0.20	5, 0.20	6, 0.50	6, 0.50	7, 0.25
Chilli	16 August (33)	4, 0.40	6, 0.40	4, 0.80	4, 0.80	3, 0.40
Groundnut(R)	1 November (44)	3, 0.20	3, 0.20	2, 0.80	4, 0.60	5, 0.20
Sorghum(R)	1 November (44)	3, 0.20	3, 0.20	2, 0.55	4, 0.45	3, 0.20
Grams(R)	1 November (44)	3, 0.05	4, 0.05	2, 0.40	4, 0.35	2, 0.20

and other crops are irrigated by furrow method. The irrigation efficiency is 56% in Kharif season and 42% for Rabi season. In the net benefit calculation, cost of cultivation of crop with out considering the cost of water is obtained from the near by agricultural research station and market prices of yield of crops prevailing in year 2004 are considered. Agro economic parameters adopted in the study and the maximum net benefit that can be obtained for each crop are tabulated in Table 5. The variation of relative yield with net seasonal depth of irrigation and variation of marginal net benefit per unit volume with deficit irrigation is studied. The percentage of deficit irrigation at which the marginal benefit per unit volume is maximum is found to be 5% for rice, 10% for groundnut (K), groundnut(R), and sorghum(R), and 15% for grams(R). For the cash crops chilli and cotton, the marginal benefit per unit volume is declining steeply when the deficit is above 10%. With the increase of percentage of deficit, the marginal net benefit per unit volume is increasing for sorghum (K) and grams (K) as the crop yields are not very sensitive to water deficit (Srinivasa et al. 2006).

Table 3 KC values and Irrigation requirement

Crop (Season)	KC_{ini}	KC_{mid}	KC_{end}	Net Irrigation requirement (mm)
Rice(K)	1.050	1.175	0.902	470
Groundnut(K)	0.831	1.137	0.562	260
Sorghum(K)	0.835	0.958	0.489	150
Grams(K)	0.835	1.016	0.559	160
Cotton(K)	0.814	1.105	0.702	325
Chilli(K)	0.863	0.967	0.708	520
Groundnut(R)	0.761	1.152	0.623	440
Sorghum(R)	0.761	1.002	0.582	345
Grams(R)	0.761	1.056	0.625	360

Table 4 Area and irrigation constraints

Crop (Season)	Sub Area-1 (thousand ha)		Sub Area-2 (thousand ha)	
	Max.	Min.	Max.	Min.
Rice-1(K)	103.5	50	85	50
Rice-2(K)	103.5	50	85	50
Groundnut(K)	40	–	40	–
Sorghum(K)	80	–	80	–
Grams(K)	100	–	100	–
Cotton	100	–	100	–
Chilli	40	–	40	–
Groundnut (R)	40	–	40	–
Sorghum (R)	50	–	50	–
Grams (R)	80	–	80	–

Daily inflows entering into the reservoir during the period 1967–2003 (37 years) are used for determining weekly water availability. The data is fitted into normal distribution by Box-Cox transformation. The expected values of weekly water available for probability of exceedences of 90%, 85%, 80% and 75% are estimated from the fitted distribution and are shown in Table 6. Alternative states of initial storages of reservoir 250 MCM, 500 MCM, 750 MCM, 1000 MCM and 1250 MCM are considered for planning purpose.

Results and discussion

Optimal cropping patterns, water allocations and net annual benefits obtained from the LP model for various combinations of weekly water availability levels and initial storages states of reservoir considered, are presented in Table 7.

Table 5 Agro economic parameters

Crop (Season)	Max. yield (kg/ha)	Market price (Rs.[a]/ kg)	Cost of cultivation (Rs./ha)	Net benefit (Rs./ha)
Rice(K)	5400	5.65	10900	18045
Groundnut(K)	1500	14.00	7000	12987
Sorghum(K)	3000	5.00	5000	9657
Grams(K)	1300	14.10	5000	12630
Cotton(K)	3000	15.30	20520	24523
Chilli(K)	3200	22.00	42325	27389
Groundnut(R)	2500	14.00	7000	26743
Sorghum(R)	3000	5.00	5000	9200
Grams(R)	1300	14.10	5000	12187

[a] 1 US $=Rs.45 (Rupees of Indian currency)

Table 6 Expected weekly inflows into the reservoir

Standard week	λ	Skewness	Kurtosis	Chi	75% PE (MCM)	80% PE (MCM)	85% PE (MCM)	90% PE (MCM)
1	0.10	0.06	2.48	2.67	94.2	84.0	73.3	61.7
2	0.25	-0.00	2.26	0.89	87.8	77.3	66.2	54.0
3	0.45	-0.01	2.70	3.10	80.8	68.4	55.4	41.1
4	0.50	0.06	2.99	1.78	94.5	80.5	65.5	48.8
5	0.15	-0.44	2.89	4.89	77.2	65.9	54.6	42.7
6	0.15	-0.31	2.69	3.56	78.5	67.6	56.5	44.8
7	0.20	-0.07	2.10	9.78	75.9	65.2	54.3	42.7
8	-0.15	-0.55	2.99	7.56	68.3	59.5	50.9	42.0
9	-0.05	-0.24	2.41	9.33	62.8	53.7	44.8	35.8
10	0.55	0.34	2.32	16.89	66.8	51.6	36.2	20.4
11	0.40	-0.03	2.71	9.33	55.0	43.1	31.3	19.5
12	0.35	-0.14	3.19	11.11	48.2	37.7	27.4	17.4
13	0.55	0.20	2.51	6.67	46.7	34.4	22.2	10.4
14	0.20	-0.05	3.12	4.00	38.8	31.0	23.5	16.2
15	-0.05	0.06	2.11	4.44	44.6	38.7	32.8	26.7
16	0.45	-0.03	3.38	3.11	22.6	16.5	10.7	5.3
17	0.40	0.48	4.36	3.56	20.2	15.4	10.8	6.4
18	0.40	-0.01	3.19	4.00	8.2	5.6	3.3	1.3
19	0.35	-0.00	3.27	8.44	4.0	2.2	0.9	0.2
20	0.35	0.81	4.74	6.22	4.3	1.9	0.5	0.0
21	0.35	0.07	3.66	1.33	9.5	6.2	3.4	1.3
22	0.40	0.50	2.71	1.78	5.3	2.5	0.7	0.0
23	0.30	-0.18	2.62	8.44	11.9	7.6	4.1	1.5
24	0.25	-0.14	3.44	4.00	11.1	6.1	2.7	0.7
25	0.30	-0.03	2.77	6.22	43.6	30.3	18.7	9.1
26	0.30	0.15	4.09	3.11	77.4	56.8	38.1	21.2
27	0.40	-0.00	3.53	4.00	164.2	124.3	85.9	49.1
28	0.30	0.07	3.80	5.33	260.2	191.0	127.9	71.3
29	0.35	0.43	3.94	8.44	315	234.9	159.7	90.1
30	0.30	0.16	3.63	2.67	466.0	365.7	269.0	174.8
31	0.40	-0.09	3.37	7.11	707.3	561.4	416.1	269.0
32	0.25	-1.17	5.77	9.78	580.0	442.1	314.1	195.2
33	0.35	-0.45	2.81	7.56	891.0	716.7	543.5	367.7
34	0.35	-0.02	2.82	4.44	842.7	675.6	510.0	342.5
35	0.45	-0.03	3.20	3.11	743.3	591.4	438.1	280.5
36	-0.20	-1.00	4.94	6.67	561.7	484.3	409.7	334.4
37	0.05	-0.44	2.72	9.33	595.9	514.0	432.1	346.6
38	0.20	0.05	3.49	7.11	431.2	347.4	266.7	187.3
39	-0.25	-0.85	4.44	6.67	412.3	351.5	294.2	237.7
40	0.15	-0.38	3.25	7.56	474.8	380.2	290.6	204.0
41	-0.05	-069	4.38	4.89	510.4	433.1	358.3	282.9
42	-0.10	-1.38	8.86	8.44	351.0	295.9	243.4	191.4
43	0.20	-0.00	6.03	8.89	271.9	219.3	168.6	118.6

Table 6 (continued)

Standard week	λ	Skewness	Kurtosis	Chi	75% PE (MCM)	80% PE (MCM)	85% PE (MCM)	90% PE (MCM)
44	0.05	-0.05	5.41	6.22	240.2	203.0	166.5	129.3
45	-0.20	-0.94	6.94	9.33	227.7	205.9	183.6	159.5
46	0.05	0.05	3.30	4.00	196.3	176.0	154.9	131.8
47	-0.10	0.01	4.53	4.44	166.2	150.1	133.4	115.3
48	0.15	0.42	7.86	9.78	140.1	121.6	102.7	82.5
49	-0.25	-018	3.01	5.78	131.7	118.8	105.6	91.5
50	0.80	0.08	1.97	3.56	133.5	115.6	95.4	71.2
51	0.35	-0.21	3.04	2.67	106.9	94.0	80.3	65.0
52	0.20	-0.02	2.60	1.33	111.7	99.1	85.9	71.2

From the results obtained, it is evident that the total annual benefit and total allocated area is higher with water availability of PE 75% when compared with that of PE 90% for all states of initial storage of reservoir. Variation of total benefit and total cropped area with the initial storage of reservoir is shown in Fig. 2. and Fig. 3. respectively. From figures, it can be observed that feasible solution is possible only when the initial storage is 300 MCM, 500 MCM, 600 MCM and 750 MCM for 75% PE, 80% PE, 85% PE and 90% PE of expected weekly inflows respectively. Impact on cropping pattern with the change in initial storage of reservoir for 75% reliable weekly inflows into the reservoir is shown in Fig. 4.

At a level of 75% water availability, area of crops chilli, cotton, grams(K) and groundnut(R) are confined to their maximum limits for all states of initial storage of reservoir considered. This is due to the fact that net benefit per hectare is high in case of chilli, cotton, groundnut(R) and low water requirement in case of grams(K) even though net benefit is not attractive. When the initial storage is less than 300 MCM, no feasible solution is obtained from the model as the water available is not sufficient enough to cultivate the minimum area imposed for rice. With the increase of initial storage of reservoir from 500 MCM to 1000 MCM, acreage of rice and groundnut(K) is improved and the net benefit is improved from 19,810 to 20,142 million rupees. All crops are irrigated with full irrigation except for grams(R) as it is more resistant to water deficit. Results indicate that there is no change in the area and water allocation, even if the initial storage of reservoir is greater than 1000 MCM. This is due to the fact that total annual water allocated to each sub area reaches the restriction imposed on maximum water allowed to use. It is also observed from the results, with the increase of availability of water at the beginning of the irrigation season, the acreage of rice and groundnut(K) is increasing while that of sorghum(K&R) and grams(R) is decreasing as they can be grown with low water requirement. Similar trend is observed at 85% and 80% reliable weekly inflows.

At 90% reliable level of water availability, no feasible solution is found when the initial storage is less than 750 MCM, as the available water could not satisfy the water requirement of rice for the minimum area imposed. Sorghum(R) and grams(R) do not appear in the irrigation plan and the area occupied by the rice is limited to its minimum area imposed because it is more water consuming crop with respect to its net return. One can see

Table 7 Area and water allocation obtained from the model

P.E (%)	S_{ini}	Sub Area	Acreage (1000 ha) and water (MCM) allocated to each crop									
			Kharif Season					Two seasonal		Rabi Season		
			Rice-1	Rice-2	Groundnut	Sorghum	Grams	Chilli	Cotton	Groundnut	Sorghum	Grams
90	750	1	50(415.7)*	50(380.3)*	0	80(194.4)*	100(133.1)*	40(231.8)	0	39.6(415.4)	0	0
		2	50(419.5)	50(383.9)	0	80(194.4)*	100(179.7)*	30(173.8)	0	40(419.3)	0	0
	1000	1	50(419.5)	50(383.9)	40(186.7)	80(213.7)	100(133.1)*	40(231.8)	32.3(299.6)	0	0	0
		2	50(419.5)	50(383.9)	40(186.7)	80(213.7)	100(133.1)*	30(173.8)	36.8(341.7)	1.51(15.8)	0	0
	1250	1	50(419.5)	50(383.9)	40(186.7)	80(213.7)	100(133.1)*	40(231.8)	42.5(394.1)	0	0	0
		2	50(419.5)	50(419.5)	40(186.7)	80(213.7)	100(133.1)*	30(173.8)	36.8(341.7)	10.5(110.4)	0	0
85	750	1	50(419.5)	50(419.5)	24.6(114.7)	80(213.7)	100(133.1)*	40(231.8)	100(928.2)	10.5(109.8)	0	0
		2	50(419.5)	50(419.5)	26.8(125.1)	80(213.7)	100(282.4)*	30(173.8)	50(464.1)	40(419.3)	0	6.4(52.8)
	1000	1	50(419.5)	50(419.5)	40(186.7)	80(213.7)	100(133.1)*	40(231.8)	90.5(839.7)	21.2(221.8)	0	0
		2	50(419.5)	50(419.5)	40(186.7)	31.8(85)	100(229.2)*	30(173.8)	50(464.1)	40(419.3)	0	0
	1250	1	50(419.5)	50(419.5)	40(186.7)	80(213.7)	100(133.1)*	40(231.8)	90.5(839.7)	30.2(316.7)	0	0
		2	62.5(525)	62.5(525)	40(186.7)	19.2(51.38)	100(252.2)*	30(173.8)	50(464.1)	40(419.3)	0	0
80	500	1	50(419.5)	50(419.5)	0	80(213.7)	100(282.4)*	40(231.8)	100(928.2)	40(419.3)	0	39.2(322.3)*
		2	50(419.5)	50(419.5)	13.9(56.5)*	80(213.7)	100(305.7)*	30(173.8)	50(464.1)	40(419.3)	9.3(76.3)	80(688.2)
	750	1	50(419.5)	50(419.5)	40(186.7)	62.4(166.7)	100(282.4)*	40(231.8)	100(928.2)	40(419.3)	0	26.4(217.5)*
		2	50(419.5)	50(419.5)	40(186.7)	31.8(84.9)	100(289.6)*	30(173.8)	50(464.1)	40(419.3)	0	73.8(607.2)*
	1000	1	50(419.5)	50(419.5)	40(186.7)	19.5(52)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	9.0(74.4)*
		2	57.2(479.7)	57.2(479.7)	40(186.7)	24.6(65.8)	100(306.6)	30(173.8)	50(464.1)	40(419.3)	0	78.4(645.3)*
	1250	1	50(419.5)	50(419.5)	40(186.7)	19.5(52)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	20.6(169.7)*
		2	81.8(686.4)	81.8(686.4)	40(186.7)	0	100(306.6)	30(173.8)	50(464.1)	40(419.3)	0	72.9(599.7)*

Table 7 (continued)

P.E (%)	S_{ini}	Sub Area	Acreage (1000 ha) and water (MCM) allocated to each crop									
			Kharif Season					Two seasonal		Rabi Season		
			Rice-1	Rice-2	Groundnut	Sorghum	Grams	Chilli	Cotton	Groundnut	Sorghum	Grams
75	500	1	50(419.5)	50(419.5)	30.5(142.2)	80(213.7)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	80(665.4)*
		2	50(419.5)	50(419.5)	40(186.7)	50.6(135.2)	100(306.6)	30(173.8)	50(464.1)	40(419.3)	50(408.8)	80(688.2)
	750	1	50(419.5)	50(419.5)	40(186.7)	21.4(57.2)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	52.1(428.4)*
		2	50(419.5)	50(419.5)	40(186.7)	31.8(84.9)	100(306.6)	30(173.8)	50(464.1)	40(419.3)	41.9(342.3)	80(688.2)
	1000	1	50(419.5)	50(419.5)	40(186.7)	19.5(52)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	50.9(418.6)*
		2	85(713.1)	85(713.1)	36.8(171.8)	0	100(306.6)	30(173.8)	50(464.1)	40(419.3)	18.2(148.5)	80(688.2)
	1250	1	50(419.5)	50(419.5)	40(186.7)	19.5(52)	100(306.6)	40(231.8)	100(928.2)	40(419.3)	0	50.9(418.6)*
		2	85(713.1)	85(713.1)	36.8(171.8)	0	100(306.6)	30(173.8)	50(464.1)	40(419.3)	18.2(148.5)	80(688.2)

Note: S_{ini} – Initial Storage of Reservoir in MCM and values in parenthesis represents water allocated in MCM

* - Deficit Irrigation

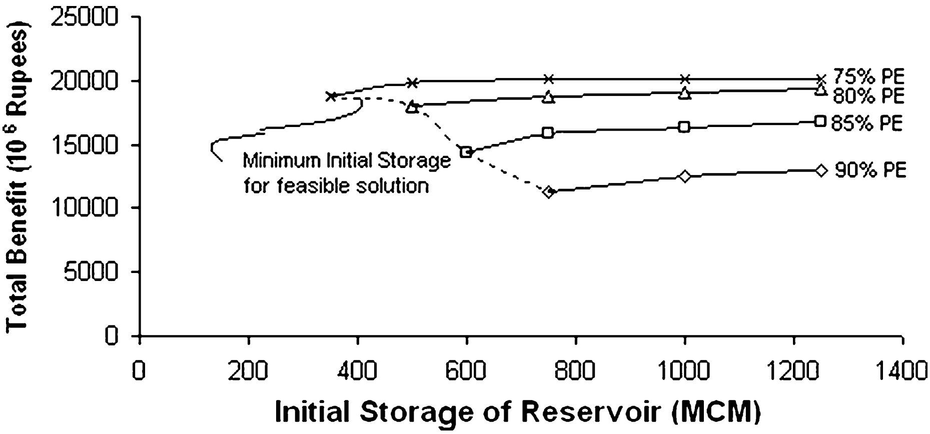

Fig. 2 Variation of total benefit with initial storage for different PE's

from the results obtained, that sorghum(K) and grams(K) are cultivated under deficit irrigation while chilli is cultivated under full irrigation occupying maximum areas imposed, as sorghum(K) and grams(K) are more resistant to water deficit while chilli is sensitive. It can also be observed that area occupied by groundnut(K) and cotton is increasing with the increase of initial storage of reservoir.

From the results obtained, variation of reservoir storage for various levels of water availability is studied. Reservoir storage and release rule curves are prepared which are useful to project authorities in guiding the reservoir release to be made or storage to be maintained in the reservoir. Rule curves for storage and release from reservoir obtained

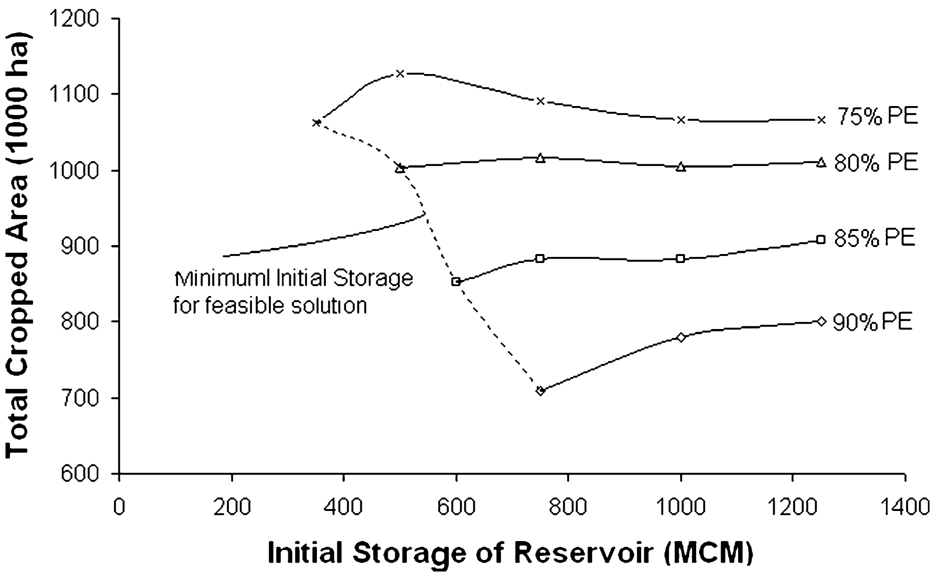

Fig. 3 Variation of total area with initial storage for various levels of expected inflows

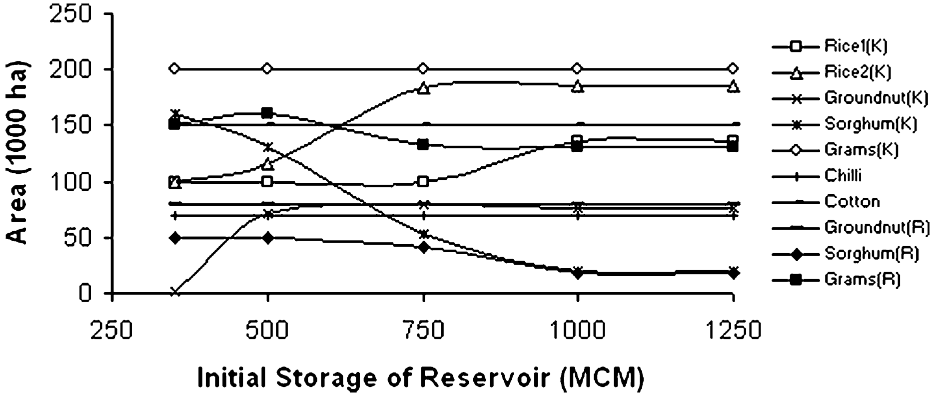

Fig. 4 Cropping pattern at 75% PE

from the planning model is shown in Fig. 5 and Fig. 6 respectively. From Fig. 5, it can be observed that the active storage is almost becoming zero at 30th week and is reaching maximum at 44th week. Carry over year storage is found to be equal to imposed minimum limit of 1000 MCM for 90%, 85% and 80% reliable inflows while it is 2,120 MCM for 75% reliable flows. It is evident from Fig. 6 that releases in the early weeks of reservoir operation are maximum as irrigation demand is peak and no releases are made from 9th week to the end of the year as no crops are grown during the same period.

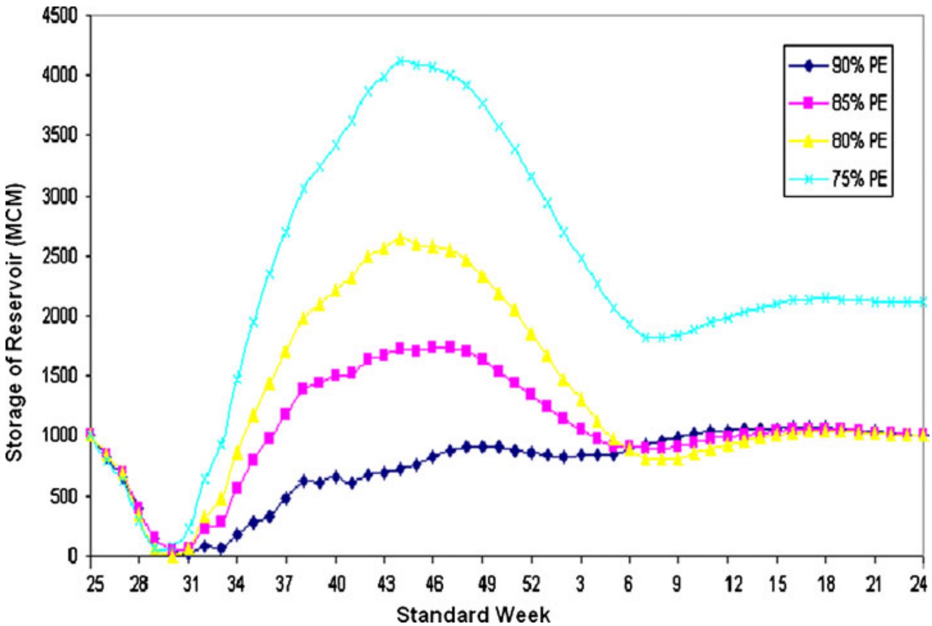

Fig. 5 Variation of reservoir storage with standard weeks

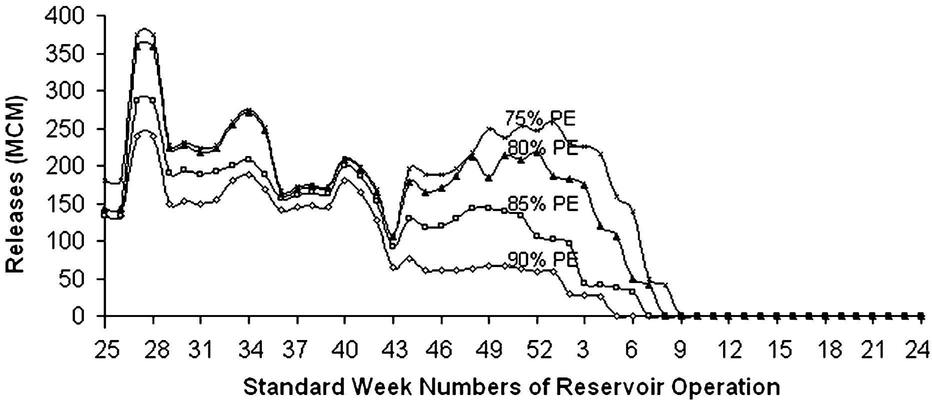

Fig. 6 Weekly releases from reservoir for various levels of expected inflows

Summary and conclusions

A model is developed for optimal irrigation planning and demonstrated through a case study. Crop water requirements are estimated by Penman-Monteith methodology. Optimal allocations of land and weekly releases are made for all crops grown in a year by running LP allocation model maximizing the annual net benefit from the project at different reliability levels of weekly water availability and initial storage states of reservoir. The results obtained are discussed. Following conclusions can be drawn for the study area based on the results obtained from the model.

(i) Results reveal that initial storage of reservoir at the beginning of the season influences in deciding the cropping pattern and water allocations. Model suggests a minimum initial storage of 750 MCM, 600 MCM, 500 MCM and 300 MCM at 90%, 85%, 80% and 75% reliable weekly inflows into the reservoir respectively. It is also found that at 75% PE, minimum initial storage of 1000 MCM is required to get maximum annual benefit. Hence it seems appropriate to maintain a minimum carry over year storage of 1000 MCM.

(ii) When the water available is low, planning model recommends deficit irrigation for sorghum(K) and grams(K) with maximum permitted area under cultivation while keeping the area occupied by rice at its minimum limit. Hence, irrigation managers and farmers are advised to adopt low water consuming crops with maximum area under deficit irrigation, when water availability is low.

The study indicates that model presented can be used to determine the optimal water resources allocation and optimal planting of various crops grown in a year. As the problem is solved by linear programming, large number of variables and linear constraints can be handled efficiently. The model can be adopted as planning model of storage based irrigation system in arid and semi-arid areas for better water management. The uncertainty of inflows entering into the reservoir is accounted in the model considering the probability of exceedence of weekly flows. However, the randomness of rainfall occurrence, as well as amount and duration are not taken into account and irrigation requirements are treated as deterministic in the model.

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