Optimal Irrigation Planning under Water Scarcity

A. Srinivasa Prasad[1]; N. V. Umamahesh[2]; and G. K. Viswanath[3]

Abstract: In this study optimal irrigation planning strategies are developed for the Nagarjuna Sagar Right Canal command in the semiarid region of South India. The specific objective of the study is to allocate the available land and water resources in a multicrop and multiseason environment and to obtain irrigation weeks requiring irrigation of a fixed depth of 40 mm. The problem is solved in four stages. First, weekly crop water requirements are calculated from the evapotranspiration model by the Penman-Monteith method. Second, seasonal crop water production functions are developed using the single-crop intraseasonal allocation model for each crop in all seasons. Third, allocations of area and water are made at seasonal and interseasonal levels by deterministic dynamic programming, maximizing the net annual benefit from the project. And fourth, once optimal seasonal allocations have been attained, irrigation scheduling is performed by running a single-crop intraseasonal allocation model. Optimal cropping pattern and irrigation water allocations are then made with full and deficit irrigation strategies for various levels of probability of exceedance of the expected annual water available. The results reveal that the optimization approach can significantly improve the annual net benefit with a deficit irrigation strategy under water scarcity.

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Introduction

Competition for water is increasing rapidly. Water shortage is a worldwide problem for which the only solution is to make efficient use of water in agriculture. Therefore, a better understanding of water requirements and better management of irrigation water will result in large benefits. When irrigation water is insufficient, appropriate scheduling can increase crop yields. A deficit occurring at a certain stage of crop growth may cause a greater reduction in yield than would the same deficit at other growth stages. As the crop water response to water deficits 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 at a seasonal level and to each season at an interseasonal level. The strategy of allocation of land and area at each level is to maximize net income from the project.

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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 a single-crop situation (Bras and Cordova 1981; Rao et al. 1988). A number of researchers have addressed the problem of allocation of a limited water supply for irrigation in a multicrop environment (Rao et al. 1990; Sunantara and Ramirez 1997; Paul et al. 2000; Reca et al. 2001; Teixeira and Marino 2002; Umamahesh and Raju 2002; Gorantiwar and Smout 2003; Smout and Gorantiwar 2005).

In essence the problem addressed in the present study is to decide cropping pattern and irrigation weeks requiring irrigation of a fixed depth of 40 mm considering yield response to water deficits. The purpose of this paper is to develop a multilevel optimization model by dynamic programming that can be used as a planning tool for allocating the annual available limited water and land at various levels, maximizing the annual net benefit. In this approach, an attempt has been made to incorporate allocation of resources at an interseasonal level, that is, allocating the annual available water and land among seasons and then reallocating the water and land among crops in each season. The seasonal depth of water allocated to each crop is distributed optimally among intraseasonal periods, maximizing the yield. The model developed is demonstrated by applying it to the Nagarjuna Sagar Right Canal (NSRC) command area in the state of Andhra Pradesh in India.

Study Area

The Nagarjuna Sagar Right Canal (NSRC) project examined in the present study is located on the river Krishna in the state of Andhra Pradesh in India (Fig. 1). The length of the main canal is 203 km and its designed discharge is 312 m^3/s. The existing command area under the NSRC project is about 0.45 million ha and falls under a semiarid tropical region with an average annual

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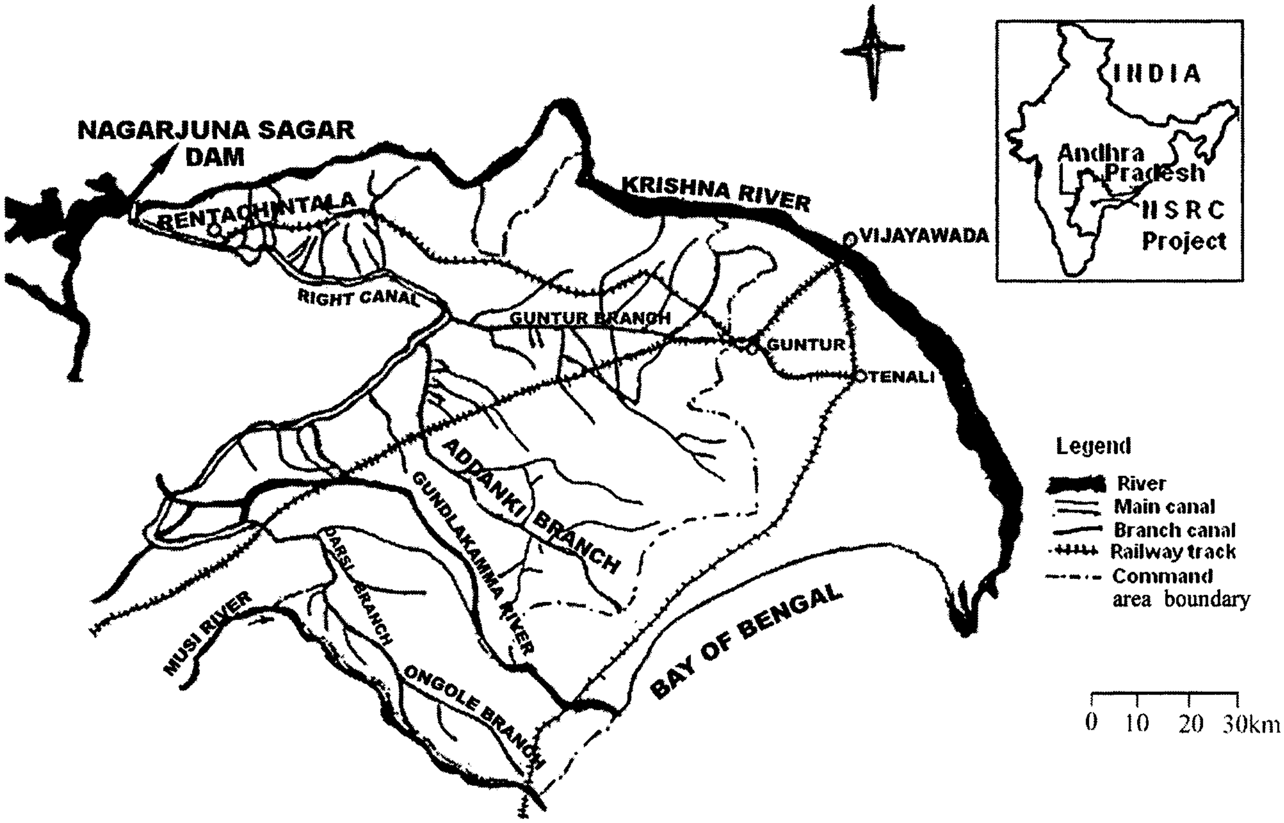

Fig. 1. Location and layout of Nagarjuna Sagar Right Canal project.

rainfall of 938 mm, two-thirds of which occurs during the period of June to October. However, the area experiences prolonged dry spells during the same period, which are critical for the survival of crops. The soils in the area are dark grey-brown to black deep clay with fine to very fine texture (Sarma and Rao 1997).

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. The major crops grown are rice, groundnut, sorghum, and grams in the Kharif season and groundnut, sorghum, and grams in the Rabi season, as well as chilli and cotton as two seasonal crops. In the initial years, when the 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 the Kharif season, as it is the staple food of the local people. The command area witnessed a 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 u/s irrigation projects on the Krishna River. This necessitates the adoption of optimal irrigation planning.

Model Formulation

It is assumed that in the case of an insufficient total water supply, the limited water and land should be allocated to different seasons and then allocated to different crops in each season. When a given amount of water is allocated to a crop, it is necessary to optimally distribute the amount of water through different intraseasonal periods. In this way, optimized procedures for land and water allocations are ensured to maximize the annual net benefit of an irrigation scheme. The model is developed for determining optimal cropping pattern and irrigation scheduling in the multicrop and multiseason environment in the study area. The complex problem is decomposed and solved stagewise, leading to an optimal solution. Fig. 2 shows the schematic representation of the whole procedure.

Evapotranspiration Model

Evapotranspiration (ET) is estimated by adopting a two-step procedure. In the first step, reference evapotranspiration (ET_o) is estimated by adopting the Penman-Monteith methodology based on long-term monthly averaged daily values of meteorological data and in the second step, weekly crop coefficients (K_c) are estimated for each crop using Food and Agricultural Organization of the United Nations (FAO) guidelines (Allen et al. 1998). Weekly maximum evapotranspiration (ETM) is calculated as $ETM = K_c\ ET_o$.

Single-Crop Intraseasonal Allocation Model

When water supplies are limited, potential yields of a crop cannot be obtained as the full irrigation requirements of the crops for the entire season cannot be met by the available water supply. For this case, evidence from field and laboratory experiments has indicated that crops respond differentially to water allocation at different times of the growing season.

Yield Response to Water Deficit

When crop water requirements are fully met from the available water supply, then weekly actual evapotranspiration (ETA) takes place equal to the rate of ETM. When the water supply is

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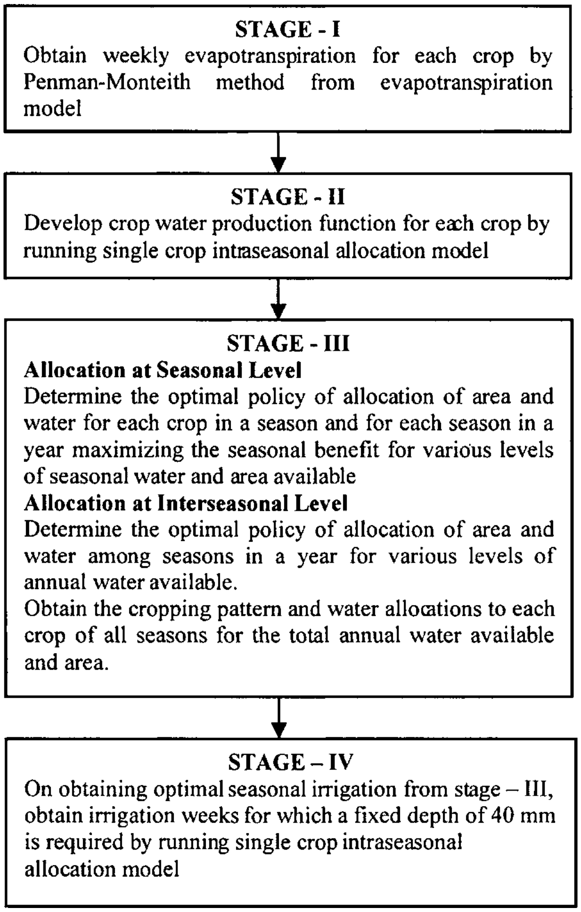

Fig. 2. Schematic representation of model development.

insufficient, ETA is less than ETM (Doorenbos and Kassam 1979). The reduction in the yield with the water deficit is expressed as

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y\left(1 - \frac{\text{ETA}}{\text{ETM}}\right) \tag{1}$$

where Y_a=actual yield with the available water; Y_m=maximum yield that can be obtained when there is no limitation of water; and K_y=yield response factor.

Weekly Actual Evapotranspiration

The intraseasonal period considered in the present study is a week. Beyond the depletion of the fraction (p) of the maximum total available soil water (SaD), the rate of ETA will fall below the rate of ETM and will depend on the remaining soil water and maximum evapotranspiration rate (Doorenbos and Kassam 1979). Total available water (TAW) in the root zone, restricting it to a maximum value equal to SaD, is calculated as

$$\text{TAW} = \text{IW1} + R_e + W_b \tag{2}$$

where IW1=irrigation water applied; R_e=effective rainfall during the time period; and W_b=available soil water in the root depth at the beginning of the time period.

If $\text{TAW} \geqslant (1-p)SaD$,

$$\text{ETA} = \text{TAW} - (1-p)SaDe^{[\text{TAW}-(1-p)SaD-\text{ETM}]/(1-p)SaD} \tag{3}$$

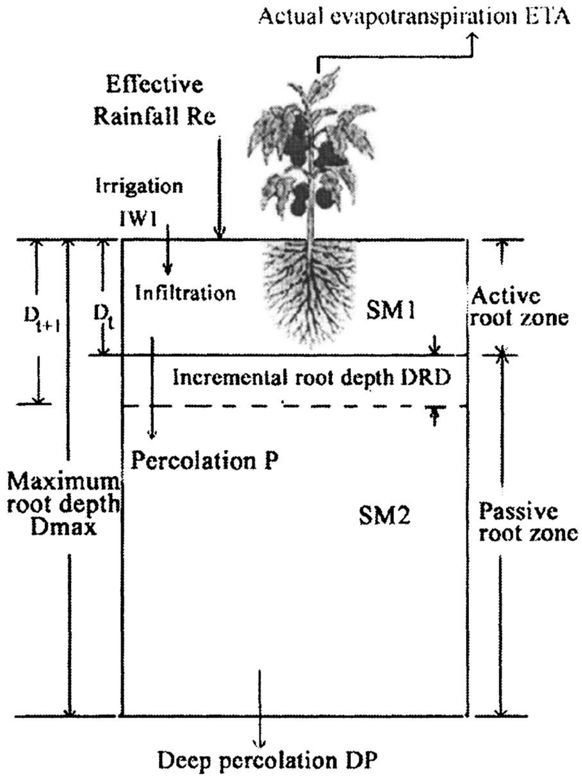

Fig. 3. Components of soil water balance model.

If $\text{TAW} < (1-p)SaD$, $\quad \text{ETA} = \text{TAW}[1 - e^{-\{\text{ETM}/(1-p)SaD\}}]$ (4)

where ETA and ETM=weekly values of actual and maximum evapotranspiration in millimeters, respectively.

Soil Water Balance Model

A two-layer soil water balance model (Hajilal et al. 1998) is adopted in the present study to calculate the soil moisture at the end of each intraseasonal period. The depth of the soil reservoir (D_t) is limited by the maximum depth ($D_{\max}$) to which the roots can grow. The soil reservoir is divided into two layers (Fig. 3): (1) An active layer (D_t) in which roots are present at any given time t and from which both moisture extraction and drainage could occur and (2) a passive root zone below the active root zone up to $D_{\max}$. The time step of water balance is chosen as 1 week. The soil water balance in the upper layer is governed by the weekly values of effective rainfall R_{e_t}, irrigation (IW1), evapotranspiration (ETA), and percolation (P) to the second layer. The soil-water balance in the lower layer is governed by percolation (P), and the drainage out of this layer as deep percolation (DP). The soil moisture (SM) content in the active layer (SM1_{t+1}) at the beginning of the $(t+1)^{\text{th}}$ week is estimated as

$$\text{SM1}_{t+1} = \frac{\text{SM1}_t D_t + R_{e_t} + \text{IW1}_t + \text{SM2}_t(D_{t+1} - D_t) - P_t - \text{ETA}_t}{D_{t+1}} \tag{5}$$

$$P_t = R_{e_t} + \text{IW1}_t - D_t(\text{FC} - \text{SM1}_t)$$
$$= 0.0 \text{ if } P_t < 0.0 \tag{6}$$

For the passive root zone, moisture content at the beginning of the $(t+1)^{\text{th}}$ week is estimated as

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$$\mathrm{SM2}_{t+1} = \mathrm{SM2}_t + \frac{P_t - \mathrm{DP}_t}{D_{\max} - D_t} \quad (7)$$

$$\mathrm{DP}_t = P_t - (\mathrm{FC} - \mathrm{SM2}_t)(D_{\max} - D_t)$$
$$= 0 \text{ if } \mathrm{DP}_t < 0 \quad (8)$$

It is assumed that the effective rainfall and the applied irrigation in any week are distributed instantaneously and uniformly over the root zone. The applied irrigation in excess of field capacity (FC) percolates to the lower passive zone and is redistributed instantaneously in that zone. The remaining water in excess of the field capacity of the passive zone moves out of it as deep percolation.

If R is the monthly rainfall in millimeters, the effective rainfall in millimeters, is estimated as

$$R_e = 0.8R - 25 \text{ if } R \geqslant 75 \text{ mm}$$
$$= 0.6T - 10 \text{ if } R < 75 \text{ mm} \quad (9)$$

A generic root growth model (Borg and Grimes 1986) is used to calculate the root depth in millimeters as

$$D_T = D_{\max}\left[0.5 + 0.5\sin\left\{3.03\left(\frac{T}{T_{\max}}\right) - 1.47\right\}\right] \quad (10)$$

where D_T=root depth T days after planting in millimeters; and $D_{\max}$=maximum depth of roots in millimeters that can be extended $T_{\max}$ days after planting. A minimum root depth of 150 mm is taken as the soil evaporation takes place from the top 150 mm of the profile; $T_{\max}$ for all crops is taken as 85 days.

Dynamic Programming Formulation

The intraseasonal allocation model for optimal relative yield for a given crop for different possible states of seasonal water available is obtained by backward dynamic programming (BDP). In the dynamic programming problem, the intraseasonal time period (t) is taken as the stage, and the soil moisture available in the active root zone ($\mathrm{SM1}_t$) and irrigation water available (IW_t) at the beginning of intraseasonal period are considered as the state variables. If ETA is the actual evapotranspiration when an amount of irrigation water IW1 is allocated during time period t, then relative yield during the time period is expressed as

$$R_{y_t}(\mathrm{SM1}_t, \mathrm{IW1}) = \left[1 - k_y\left(1 - \frac{\mathrm{ETA}}{\mathrm{ETM}}\right)\right] \quad (11)$$

The objective function of deterministic dynamic programming (DDP) is maximization of seasonal relative yield (Y_a/Y_m) and is given as

$$\text{Maximize} \prod_{t=1}^{nt} R_{y_t}(SM1_t, IW1) \quad (12)$$

The recursive equation of the BDP problem for any time period t can be written as

$$O_{ry_t}(\mathrm{SM1}_t, \mathrm{IW}) = \mathrm{Max}[R_{y_t}(\mathrm{SM1}_t, \mathrm{IW1}) \times O_{ry_{t+1}}\{\mathrm{SM1}_{t+1}, (\mathrm{IW} - \mathrm{IW1})\}]$$
$$\text{for } t = nt-1, nt-2, \ldots \ldots \ldots 1 \quad (13)$$

and when $t=nt$

$$O_{ry_{nt}}(\mathrm{SM1}_{nt}, \mathrm{IW}) = \mathrm{Max}\{R_{y_{nt}}(\mathrm{SM1}_{nt}, \mathrm{IW1})\} \quad (14)$$

subjected to

$$0 \leqslant \mathrm{IW1} \leqslant \mathrm{IW} \leqslant \mathrm{IW}_{\max}$$

where $O_{ry_t}(\mathrm{SM1}, \mathrm{IW})$=maximum value of the objective function, when SM1=soil moisture available at the beginning of time period t and IW=water available for allocation for all time periods, starting from the last time period nt to the current time period t; $\mathrm{SM1}_{t+1}$=soil moisture at the beginning of the $(t+1)$th period obtained from Eqs. (5) and (6); and $\mathrm{IW}_{\max}$=maximum irrigation requirement.

Seasonal Crop Water Production Functions

The intraseasonal allocation model is used to determine the maximum relative yields that can be obtained from a given crop for different levels of net seasonal irrigation water. The results obtained are used to develop crop water production functions, expressing relative yield as a function of the net seasonal irrigation water, applied and fitted into a 5th degree polynomial function. Regression analysis by the least-squares method is adopted to estimate the parameters, and the general form may be expressed as

$$\frac{Y_a}{Y_m} = \sum_{i=0}^{5} a_i w^i \quad (15)$$

where Y_a=crop yield when w is the net seasonal water applied; Y_m=maximum yield of the crop when there is no water limitation; and a_i=coefficient of the ith term of the equation.

Allocation Model

Allocations of area and water are made using a multilevel approach. At the seasonal level, the optimal policy of allocation of water and area among crops grown in each season is obtained by dynamic programming using crop water production functions. Crop c of season s represents the stage of the problem, and the area and water available are considered as state variables. The objective function of this model is the maximization of the total seasonal net benefit from all crops

$$\text{Maximize} \sum_{c=1}^{nc_s} B(AC_{s,c}, RC_{s,c}) \quad (16)$$

where $B(AC_{s,c}, RC_{s,c})$=benefit in millions of rupees of Indian currency from crop c of season s and is calculated as

$$B(AC_{s,c}, RC_{s,c}) = (Y_{s,c}PC_{s,c}AC_{s,c} - PO_{s,c}A_{s,c} - P_w R_{s,c})1.0e-06 \quad (17)$$

where $Y_{s,c}$=yield in 100 kg per hectare, when the $AC_{s,c}$ area in hectares is irrigated with a seasonal gross irrigation volume of $RC_{s,c}$ million cubic meters (mcm); $PC_{s,c}$=market price of the yield in rupees per 100 kg; $PC_{s,c}$=cost of cultivation in rupees per hectare; and P_w=price of water in rupees per mcm.

Recursive equations of dynamic programming can be written as

$$\mathrm{TSB}_{s,c}(SA, SR) = \mathrm{Max}[\mathrm{Max}\{B(AC, RC) + \mathrm{TSB}_{s,c+1}(SA - AC, SR - RC)\}]$$
$$\text{for } c = nc_s - 1, nc_s - 2 \ldots \ldots \ldots 1 \quad (18)$$

and when

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$$c = nc_s,\ \mathrm{TSB}_{s,nc(s)}(SA,SR) = \mathrm{Max}[\mathrm{Max}\{B(AC,RC\ \}] \quad (19)$$

subjected to

$$AC_{\min} \leqslant AC \leqslant SA \leqslant AC_{\max}$$

$$RC_{\min} \leqslant RC \leqslant SR \leqslant RC_{\max}$$

$$\mathrm{SAMIN}_s \leqslant \sum_{c=1}^{nc_s} AC_{s,c} \leqslant \mathrm{SAMAX}_s$$

where $\mathrm{TSB}_{s,c}(SA,SR)$=maximum total benefit from all the crops, starting from the last crop nc_s to the current crop c of season s when AC and RC=area and release allocated to crop c of season s; and SA and SR=states of area and release available for allocation. In addition, $AC_{\max}$, $AC_{\min}$, $RC_{\max}$, and $RC_{\min}$=maximum and minimum limits of acreage and gross seasonal irrigation allocable to each crop, respectively. Likewise, SAMAX_s and SAMIN_s=maximum and minimum limits of area of season s.

At the interseasonal level, the annual water and area available are to be allocated among the two seasons, Kharif and Rabi, maximizing the total annual benefit from the project. The allocation problem is solved by the dynamic programming technique. Season s represents the stage of the problem, and the objective function of the model is

$$\mathrm{Maximize} \sum_{s=1}^{ns} \mathrm{TSB}_{s,1}(AS,RS) \quad (20)$$

where $\mathrm{TSB}_{s,1}(AS,RS)$=optimal benefit from season s obtained from a seasonal allocation policy when AS and RS=area and water allocated to each season; and ns=number of seasons in the planning horizon.

The recursive equation of the dynamic programming model can be written as

$$\mathrm{TAB}_s(AA,RA) = \mathrm{Max}[\mathrm{Max}\{\mathrm{TSB}_{s,1}(AS,RS) + \mathrm{TAB}_{s+1} \times (AA - AS, RA - RS)\}]$$
$$\text{for } s = ns-1, ns-2, \ldots \ldots \ldots 1 \quad (21)$$

and when $s=ns$

$$\mathrm{TAB}_{ns} = \mathrm{Max}\{\mathrm{TSB}_{ns,1}(AS,RS)\} \quad (22)$$

subjected to

$$0 \leqslant AS \leqslant AA \leqslant \mathrm{SAMAX}_s$$

$$0 \leqslant RS \leqslant RA$$

$$TA \leqslant \sum_{s=1}^{ns} AS_s$$

$$TR \leqslant \sum_{s=1}^{ns} RS_s$$

where $\mathrm{TAB}_s(AA,RA)$=maximum benefit from all seasons starting from last season ns to the current season s, when AA and RA=states of area and water available at the beginning of the season s for allocation to all seasons from the last season to the current season s. Thus, TA and TR=total annual area and release available to be allocated for all seasons, respectively.

Irrigation Scheduling Model

The optimal seasonal irrigation depth obtained from Stage III for each crop is to be allocated among intraseasonal periods of the crop by running a single-crop intraseasonal allocation model maximizing the seasonal relative yield. The intraseasonal period is taken as 1 week. An irrigation scheduling policy of fixed depth and variable intervals in multiple weeks is adopted in the present study, as the fixed depth of irrigation is preferred in large irrigation projects.

Results and Discussion

A total of nine crops of rice, groundnut, sorghum, grams including two seasonal crops chilli and cotton in Kharif season and groundnut, sorghum and grams in Rabi season are considered in the present study. Evapotranspiration model is used to obtain the ETM of all crops. Data to compute ET_o is obtained from a nearby weather station, Rentachintala (30 years of data are

Table 1. Meteorological Data and Reference Evapotranspiration from Model.

Month	Daily temparature (°C)		Daily relative humidity (%)		Relative sunshine duration	Monthly rainfall (mm)	Number of rainy days	Wind speed (kmph)	ET_o (mm/day)
	Maximum	Minimum	Maximum	Minimum					
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

Note: Station: Rentachintala, latitude: 16°33′, longitude: 79°33′, height above MSL: 106.0.

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Table 2. Basic Crop Data.

Crop (season)	Date of sowing (standard week)	Root depth (D_{max}) (mm)	Duration of growth stages in weeks and yield response factors K_y				
			Initial	Crop development	Flowering	Grain formation	Ripening
Rice (K)	1 July (27)	400	2, 1.10	5, 1.10	3, 2.40	3, 2.40	3, 0.33
Groundnut (K)	1 July (27)	1,000	3, 0.20	3, 0.20	2, 0.80	4, 0.60	3, 0.20
Sorghum (K)	16 July (29)	1,500	3, 0.20	3, 0.20	2, 0.55	4, 0.45	3, 0.20
Grams (K)	16 July (29)	1,300	3, 0.05	4, 0.05	2, 0.40	4, 0.35	2, 0.20
Cotton (K)	16 July (29)	1,500	4, 0.20	5, 0.20	6, 0.50	6, 0.50	7, 0.25
Chilli (K)	16 August (33)	1,000	4, 0.40	6, 0.40	4, 0.80	4, 0.80	3, 0.40
Groundnut (R)	1 November (44)	1,000	3, 0.20	3, 0.20	2, 0.80	4, 0.60	5, 0.20
Sorghum (R)	1 November (44)	1,500	3, 0.20	3, 0.20	2, 0.55	4, 0.45	3, 0.20
Grams (R)	1 November (44)	1,500	3, 0.05	4, 0.05	2, 0.40	4, 0.35	2, 0.20

available). The monthly mean daily ET_o (mm/day) is computed for the observed meteorological data and shown in Table 1. The entire command area is assumed to be of a single soil type, as a major portion of the area is of the black cotton type of soil. Soil storage parameters viz., field capacity and permanent wilting point (PWP) are taken as 46 and 21% v/v, respectively (Rao 1998).

Basic crop data for all crops considered are obtained from the state department of irrigation and is presented in Table 2. The growing period is divided into five general growth stages: initial, crop development, flowering, grain formation, and ripening. The duration of the crop growth stages is adjusted to an integral multiple of weeks. Crop coefficients during the initial period (Kc_{ini}) and the middle period (flowering and grain formation) (Kc_{mid}) and at the end of the ripening period (Kc_{end}) are estimated. Crop coefficient curves such as those shown in Fig. 4 are developed for all crops considered in the present study. The weekly ETM and net irrigation requirement of crops taking the normal effective rainfall into consideration are estimated; K_c values obtained from the model and net seasonal irrigation requirement of crops are presented in Table 3.

The initial soil moisture available at the beginning of the season is considered as 30% v/v; 35 discrete values of soil moisture (SM1), starting from 21 to 46% v/v with an increment of 0.75, and 11 discrete values of irrigation water available (IW) at the beginning of each stage of DDP, starting from 0 to 400 mm with an increment of 40 mm, are considered as state variables in a single-crop intraseasonal allocation model. In the case of rice, the depth of standing water, including soil water, is considered as a state variable, and a presowing depth of 250 mm is taken for land preparation and transplanting purposes. A 5th degree polynomial crop-water production is developed for each crop from the single-crop intraseasonal allocation model. Crop-water production curves for various levels of net seasonal irrigation water are shown in Fig. 5.

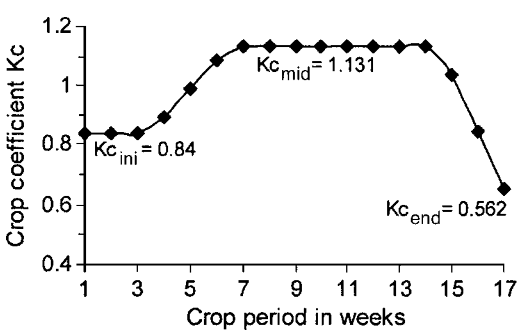

Fig. 4. K_c curve for groundnut (K).

While applying optimal allocations of water and land, upper and lower bounds on area and release are imposed considering the local requirements and food habits of the people (Table 4). The maximum area available for planting is 450,000 ha for the Kharif season and the total maximum area available for both the seasons is 600,000 ha. As rice is the principal crop grown, a minimum area of 100,000 ha with a minimum net irrigation of 650 mm is considered to satisfy the local food requirements. Rice is irrigated by the flooding method and other crops are irrigated by furrow method. The irrigation efficiency is 56% in the Kharif (K) season and 42% for the Rabi (R) season.

The agroeconomic parameters adopted in the study and the maximum net benefit that can be obtained for each crop are tabulated in Table 5. The price of water is considered to be Rs. 120,000 per million cubic meters. Variation of the marginal net benefit per unit volume of water applied with a percentage deficit of irrigation requirement is shown in Fig. 6, and 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 of water applied is declining steeply when the deficit is above 10%. With the increase of percentage 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.

Table 3. K_c values and Irrigation Requirements.

Crop (season)	$K_{C_{ini}}$	$K_{C_{mid}}$	$K_{C_{end}}$	Net irrigation requirement (mm)
Rice (K)	1.050	1.175	0.902	730
Groundnut (K)	0.831	1.137	0.562	240
Sorghum (K)	0.835	0.958	0.489	160
Grams (K)	0.835	1.016	0.559	240
Cotton (K)	0.814	1.105	0.702	400
Chilli (K)	0.863	0.967	0.708	320
Groundnut (R)	0.761	1.152	0.623	440
Sorghum (R)	0.761	1.002	0.582	280
Grams (R)	0.761	1.056	0.625	400

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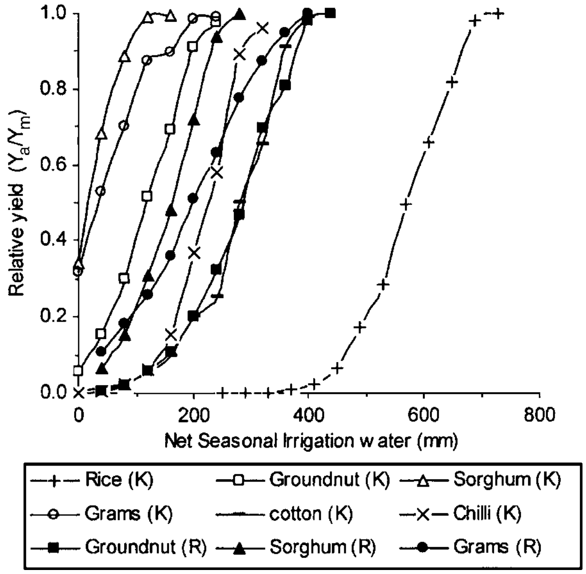

Fig. 5. Seasonal crop water production curves.

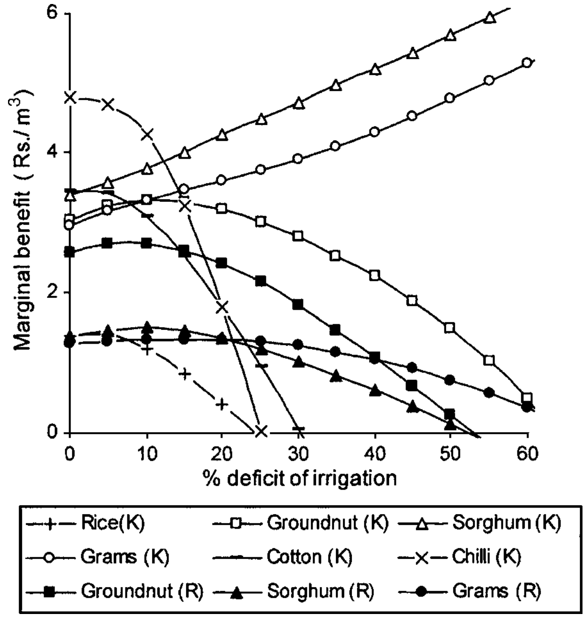

Fig. 6. Marginal benefit versus percent deficit irrigation.

Annual canal releases during the period 1967–2003 (37 years) are used for determining annual water availability. The historical data are transformed by the Box-Cox transformation and fitted to the normal distribution. The skewness coefficient and kurtosis of transformed series are calculated as −0.7374 and 3.0142, respectively. The expected annual values of water available for different probability of exceedences of 90, 80, 70, 60, and 50% are 2,920, 3,610, 4,040, 4,390, and 4,700 mcm, respectively. The values considered are 61 discrete values of the state variable for an area from 0 to 600,000 ha, with an increment of 10,000 ha, and 471 discrete values for the state variable for available water from 0 to 4,700 mcm, with an increment of 10 mcm.

The two alternative strategies considered for planning purposes due to the inadequacy of available water supplies to irrigate the entire available land are as follows:

1. Restricting to full irrigation so that the crop is not subjected to water stress, resulting in maximum yield per hectare but with limited area under irrigation; and
2. Allowing deficit irrigation, causing stress to the crop and resulting in reduced yield per hectare but with more land under irrigation.

Optimal cropping patterns, water allocations, and net annual benefits obtained from the allocation model for various combinations of annual water availability levels and management strategies considered are presented in Table 6.

Weekly irrigation requirements at the field level for each crop are assessed by running the single-crop intraseasonal allocation model on obtaining the optimal net seasonal irrigation depth from Stage III. The fixed depth of irrigation adopted for each application is 40 mm. A presowing irrigation of 40 mm is considered for the Rabi crops. Table 7 presents the weekly numbers (in standard weeks) requiring irrigation. These represent the optimal seasonal irrigation obtained from Stage III for all crops at a water availability level of 80% when Strategy 2 is adopted.

From the results obtained, it is evident that the total annual benefit and total allocated area are higher with Strategy 2 compared with Strategy 1 for all levels of water availability. When Strategy 2 is adopted, the area of planting is increased by 60,000 ha, resulting in an additional benefit of 727 million rupees at a 90% reliable level of water availability (2,920 mcm).

Table 4. Area and Irrigation Constraints.

Crop (season)	Area (1,000 ha)		Net irrigation (mm)	
	Maximum	Minimum	Maximum	Minimum
Rice (K)	220	100	730	650
Groundnut (K)	40	—	240	—
Sorghum (K)	80	—	160	—
Grams (K)	100	—	240	—
Cotton (K)	100	—	400	—
Chilli (K)	40	—	320	—
Groundnut (R)	40	—	440	—
Sorghum (R)	50	—	280	—
Grams (R)	80	—	400	—

Table 5. Agroeconomic Parameters.

Crop (season)	Maximum yield (kg/ha)	Market price (Rs./kg)	Cost of cultivation (Rs./ha)	Net benefit (Rs./ha)
Rice (K)	5,400	5.65	10,900	18,045
Groundnut (K)	1,500	14.00	7,000	12,987
Sorghum (K)	3,000	5.00	5,000	9,657
Grams (K)	1,300	14.10	5,000	12,630
Cotton (K)	3,000	15.30	20,520	24,523
Chilli (K)	3,200	22.00	42,325	27,389
Groundnut (R)	2,500	14.00	7,000	26,743
Sorghum (R)	3,000	5.00	5,000	9,200
Grams (R)	1,300	14.10	5,000	12,187

Note: 1 US$=Rs.45 (rupees in Indian currency).

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Table 6. Optimal Cropping Pattern and Water Allocation at Different Probability of Exceedance.

		Area (1,000 ha) and water (1,000 mcm) allocated										
		Kharif (wet)						Rabi (dry)				
PE	Strategy	Rice	Groundnut	Sorghum	Grams	Cotton	Chilli	Groundnut	Sorghum	Grams	Total cropped area (1,000 ha)	Total annual benefit (million rupees)
90%	1	100	30	80	70	100	40	—	—	—	420	7,425
(2.92)		1.31	0.13	0.23	0.30	0.72	0.23					
	2	100	30	80	100	100	40	30	—	—	480	8,152
		1.25	0.12	0.13	0.20	0.70	0.23	0.29				
80%	1	100	30	80	100	100	40	40	20	—	510	9,062
(3.61)		1.31	0.13	0.23	0.43	0.72	0.23	0.42	0.14			
	2	100	40	70	100	100	40	40	50	10	550	9,368
		1.26	0.16	0.14	0.32	0.72	0.23	0.40	0.30	0.08		
70%	1	100	40	70	100	100	40	40	50	20	560	9,618
(4.04)		1.31	0.18	0.20	0.43	0.72	0.23	0.42	0.34	0.20		
	2	100	40	70	100	100	40	40	50	60	600	9,944
		1.26	0.16	0.14	0.35	0.72	0.23	0.40	0.30	0.48		
60%	1	100	30	80	100	100	40	40	50	60	600	10,068
(4.39)		1.31	0.13	0.23	0.43	0.72	0.23	0.42	0.34	0.58		
	2	120	40	50	100	100	40	40	40	70	600	10,260
		1.52	0.16	1.10	0.38	0.72	0.23	0.40	0.24	0.63		
50%	1	120	40	50	100	100	40	40	30	80	600	10,333
(4.70)		1.57	0.18	0.15	0.43	0.72	0.23	0.42	0.20	0.77		
	2	150	40	20	100	100	40	40	40	70	600	10,508
		1.90	0.16	0.04	0.38	0.72	0.23	0.40	0.24	0.63		

Note: PE=probability of exceedance and expected annual available water per 1,000 mcm (shown in parentheses).

For all levels of water availability, the area of the commercial crops chilli and cotton is confined to their maximum limits for both strategies, as the marginal net benefit per hectare is high.

Full irrigation is recommended for these two crops up to an 80% reliability level, as the marginal net benefit per cubic meter of water applied is declining steeply with the increase in the percentage of deficit irrigation. No allocations are made to the Rabi (dry) season when the available water is at a 90% reliable level with Strategy 1. Note also that maximum acreage is allocated to grams in the Kharif season with deficit irrigation for all levels of water availability as yield response to water deficit is not very sensitive. Acreage of rice is restricted to the minimum imposed limit of 100,000 ha for both strategies when the annual water available is less than 4,390 mcm, and it is marginally increased to 150,000 ha at a 50% reliable level with Strategy 2. This discrimination in allocating low acreage to rice is due to its lowest value of marginal net benefit per unit volume of irrigation water, even though the net benefit per hectare is moderate.

Summary and Conclusions

A model is developed for optimal irrigation planning and demonstrated through a case study. Crop water requirements are estimated from the evapotranspiration model, and crop water production functions are developed from a single-crop intraseasonal allocation model. Optimal allocations of land and water are made at seasonal and interseasonal levels by running an allocation model maximizing the annual net benefit from the project at different reliability levels of water availability, and the results obtained are discussed.

The following conclusions can be drawn for the study area based on the results obtained from the model:

1. Results reveal that with deficit irrigation there is a substantial increase in net annual benefit and total cropped area, especially when the available water is low.

Table 7. Irrigation Weeks at 80% Level of Water Availability with Strategy 2.

Crop (season)	Net seasonal irrigation depth (mm)	Standard number of weeks requiring irrigation of fixed depth (40 mm)
Rice (K)	690[a]	27, 28, 30 to 35, 37, 38 and 40
Groundnut (K)	240	27 to 31 and 33
Sorghum (K)	120	29 to 31
Grams (K)	160	29, 32, 35, and 37
Cotton (K)	400	29, 30, 31, 33, 35, 39, 44, 49, 51, and 1
Chilli (K)	320	33 to 36, 46, 48, 50, and 51
Groundnut (R)	440[b]	45 to 47, 49 to 51, 2, 3, 5, and 6
Sorghum (R)	240[b]	45 to 47, 52, and 1
Grams (R)	320[b]	45, 48 to 52, and 1

[a]Includes presowing depth of 250 mm for land preparation.
[b]Includes presowing depth of 40 mm.

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2. When the water available is low, the planning model recommends that the area occupied by rice be at its minimum limit while that for chilli and cotton is at their maximum limits. The area allocated to sorghum is increasing with the decrease of water availability. Hence, irrigation managers and farmers are advised to adopt low water-consuming crops with a maximum area under deficit irrigation when water availability is low.

The study indicates that the model presented can be used to determine the optimal water resources allocation as well as the optimal planting area across various crops in a season and among various seasons in a year. As the problem is solved by decomposing it into various levels (interseasonal, seasonal, and intraseasonal), the obstacles of dimensions are overcome, and the model can be adopted in arid and semiarid areas for better water management.

The command area of a large irrigation system may include several soil types on which different crops are to be grown. Soil properties are assumed to be uniform over the entire command area in the case study to simplify the numerical procedure, but this is not a limitation of the model, and the allocation of area and water to each crop grown on each soil type can be made by considering the soil type as an additional stage in the dynamic programming problem. The randomness of rainfall occurrence, as well as the amount and duration, are not taken into account and are treated as deterministic in the model. Further, the model can be extended to a real-time integrated reservoir operation and irrigation scheduling model by incorporating a reservoir component and by updating the forecasted meteorological and hydrological input data.

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Notation

The following symbols are used in this paper:

AA = state variable of area available for allocation among seasons;
AC_{max}, AC_{min} = maximum and minimum limits of allocable area to crop c of season s;
$AC_{s,c}$ = area allocated to crop c of season s;
AS = area allocated to season;
D_{max} = maximum root depth to which roots can grow;
DP_t = deep percolation out of passive layer;
D_t = depth of active layer;
ETA = weekly actual evapotranspiration;
ETM = weekly maximum evapotranspiration;
ET_o = reference evapotranspiration;
FC = field capacity of soil;
$IW1$ = net irrigation water applied;
IW_t = state variable irrigation water available for allocation at beginning of time period t;
IW_{max} = maximum net irrigation requirement of crop;
K_c = crop coefficient;
K_y = yield response factor of crop during growth stage;
nc_s = total number of crops grown in season s;
ns = total number of seasons in year;
nt = total number of intraseasonal time periods of crop;
$PC_{s,c}$ = unit market price of crop c of season s;
$PO_{s,c}$ = cost per unit area for inputs other than water;
P_t = percolation into passive layer from active layer;
P_w = unit market price of water;
p = allowable soil moisture depletion factor;
R = monthly rainfall;
RA = state variable of annual gross volume of irrigation water available for allocation among seasons;
RC_{max} and RC_{min} = maximum and minimum limits of allocable gross volume of irrigation water to crop c;
$RC_{s,c}$ = gross volume of water allocated to crop c of season s;
R_e = effective rainfall;
RS = gross volume of irrigation water allocated to season;
SA, SR = state variables of area and gross volume of irrigation to be allocated among crops in season, respectively;
SAMAX_s and SAMIN_s = maximum and minimum limits of allocable area to season s, respectively;
$SM1_t$ = state of soil moisture in active layer at beginning of time period t;
$SM2_t$ = soil moisture content in passive layer at beginning of time period t;
TA = total area available to be allocated among seasons;
TR = total gross volume of irrigation water available to be allocated among seasons.
W_b = available soil water in root depth at beginning of time period;
Y_a = actual yield of crop with available water;
Y_m = maximum yield of crop that can be obtained when there is no limitation of water; and
$Y_{s,c}$ = yield of crop c of season s.

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