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Optimal Annual Allocation Model of Large Storage Based Irrigation Project by Multi Level Approach

A. Srinivasa Prasad[1*], G.K.Viswanadh[2], P.V.S. Maruthi Krishna[3] and K. Leela Krishna[3]

[1,3]Department of Civil Engineering, R.V.R. & J.C.College of Engineering, Chowdavaram, Guntur 522 019, Andhra Pradesh, India
[2] Department of Civil Engineering, JNTUH College of Engineering Hyderabad, Hyderabad 500 085, Telangana, India

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ABSTRACT

The effective management of water available for irrigation in arid and semi-arid regions has increased in importance due to limited water supply. The need for allocation of water resources optimally in a water limiting condition has already been recognized, and much research has been carried out. In the present study, an annual irrigation planning model is formulated for Nagarjuna Sagar Project command in the semi-arid region of South India dealing with optimal allocation of annual available water among command areas of each main canal taking off from the reservoir and reallocating the available land and water of each command area to different seasons of a year and finally allocating the available land and water of each season among crops grown in that season, maximizing the total annual benefit of the project. The problem is solved in three stages. In the first stage, fortnightly crop water requirements are calculated from the evapotranspiration model by Penman – Monteith method. In the second stage, seasonal crop water production functions are developed using the single crop intraseasonal allocation model for each crop of all seasons. In the third stage, allocations of area and water are made at seasonal, interseasonal and at reservoir levels by deterministic dynamic programming, maximizing the net annual benefit from the project. Optimal cropping pattern and irrigation water allocations are made with full and deficit irrigation strategies for various levels of probability of exceedences of expected annual water available and results obtained are discussed.

Key words: *Allocation of resources, Irrigation planning, Dynamic programming, Optimization model.*

Introduction

The effective management of water available for irrigation in arid and semi-arid regions has increased in importance due to limited water supply. The planning for irrigation water management in an irrigation command area consists of the preparation of an allocation plan for distribution of land and water resources to different crops, and water delivery schedules in terms of timing and amount of water delivery for the allocation plan according to the set objectives/targets. The need for allocation of water resources optimally in a water limiting condition has already been recognized, and much research has been carried out.

Several researchers formulated Linear Programming (LP) models to obtain optimal cropping pattern [Onta *et al.*, (1995), Viswanath (1995), Panda *et al.*, (1996), Mainuddin *et al.*, (1997), Singh *et al.*, (2001) & Laxmi narayan sethi *et al.*, (2002)]. Rao *et al.*,

([1]Prof., [2]Professor, [3]Associate Prof.)

(1990) Addressed the problem of allocation of a limited supply for irrigation of several crops in the same season. Optimal seasonal water and acreage allocation were defined among several crops using Dynamic Programming (DP) models in literature [Sunantara & Ramirez (1997), Paul *et al.,* (2000) and Teixeira and Marino (2002)]. The purpose of this paper is to develop an optimization model for allocating the available land and water at various levels, maximizing the annual net benefit. The objectives of the present study are (i) to obtain crop water requirements by Penman-Monteith method (ii) to develop seasonal crop water production functions (iii) to allocate the available land and water resources in multi-crop and multi-season environment. The model developed is demonstrated by applying to Nagarjuna Sagar Project (NSP) command area in the state of Andhra Pradesh in India.

Study Area

The Nagarjuna Sagar Project examined in the present study is located on the river Krishna in the state of Andhra Pradesh in India (Fig.1). The irrigation project comprises of 124.66 m height masonry dam with two canals taking off from the reservoir on either side with a design discharge of 311.3 m^3/s. The reservoir is located at16^0–34′ N and longitude 79^0–19′ E with live capacity of 5,733 MCM. The length of right canal is 203 km having 53 off takes with an ayacut of 0.4505 M ha, while the length of the left canal is 295 km having 115 off takes with an ayacut of 0.3869 M ha. This project also stabilizes irrigation under Krishna delta system and required water to Krishna delta is released through eight power units with an installed capacity to generate 810 MW of power. 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 (winter). In the initial years when entire command area was not developed, farmers were 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.

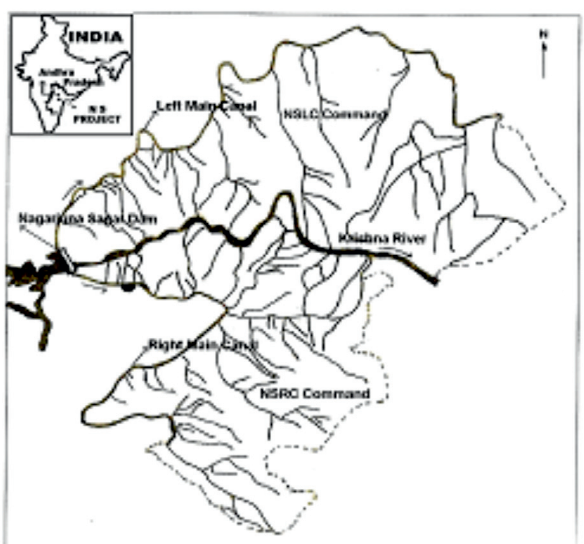

Fig. 1.Schematic Representation of Nagarjuna Sagar Project Layout

Model Formulation

It is assumed that in the case of insufficiency of total water supply, the limited annual available water from the reservoir should be allocated to main canals taking off from the reservoir. The water allocated and the land under each canal is to be optimally distributed among 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 annual net benefit of an irrigation scheme. The model is developed for determining optimal cropping pattern and seasonal depth of irrigation in multi-crop and multi-season environment in the study area. The complex problem is decomposed and solved stage wise leading to an optimal solution. Fig. 2 shows the schematic representation of the whole procedure.

Estimation of Evapotranspiration

Evapotranspiration model estimates the reference evapotranspiration by the FAO Penman-Monteith method.

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

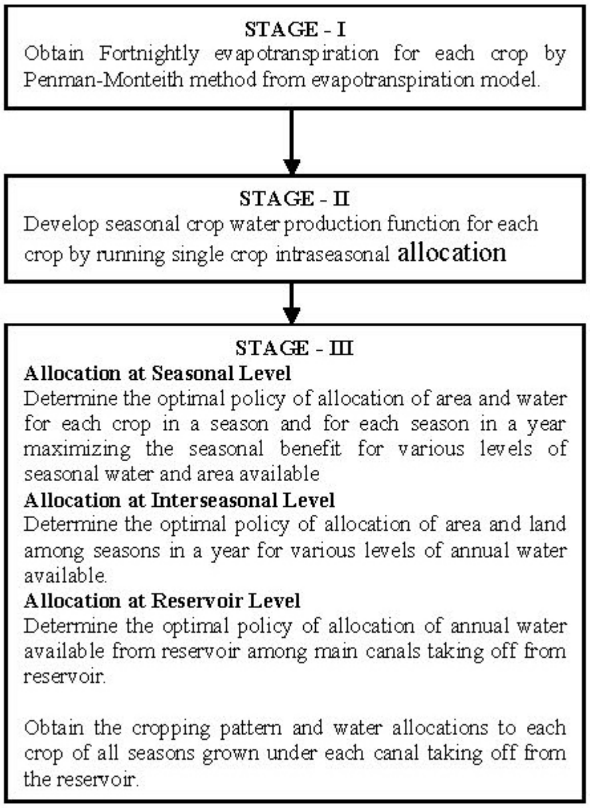

Fig. 2. Schematic Representation of Model Development

K_c values for different growth stages of crop are estimated following the procedure outlined in FAO Irrigation and Drainage paper 56 [Allen *et al.*, (1998)]. Maximum evapotranspiration (ET_m) when water supply fully meets the water requirements of the crop is related to ET_o as

$$ET_m = K_c \,.\, ET_o \qquad (2)$$

Single Crop Intraseasonal Allocation Model

When water supplies are limited, potential yields of 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 growing season.

Yield Response to Water Deficit

When crop water requirements are fully met from the available water supply, then actual evapotranspiration (ETA) takes place equal to the rate of maximum evapotranspiration (ETM). When water supply is insufficient, ETA is less than ETM [Doorenbos & Kassam (1979)]. The reduction in the yield with the water deficit is related as

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ETA}{ETM}\right) \qquad (3)$$

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

Fortnightly Actual Evapotranspiration

Intraseasonal period considered in the present study is a fortnight. Beyond the depletion of the fraction (p) of the maximum total available soil water (Sa.D), rate of actual evapotranspiration will fall below the rate of maximum evapotranspiration and it depends on the remaining soil water and on maximum evapotranspiration rate [Doorenbos & Kassam (1979)]. Total available water (TAW) in the root zone restricting its maximum value to SaD is calculated as

$$TAW = IW1 + Re + Wb \qquad (4)$$

where IW1 is irrigation water applied, Re is effective rainfall during the time period, Wb is available soil water in the root depth at the beginning of the time period.

If TAW ≥ (1-p) SaD,

$$ETA = TAW - (1-p)SaD\; e^{\frac{TAW-(1-p)SaD-ETM}{(1-p)SaD}} \qquad (5)$$

If TAW < (1-p) SaD,

$$ETA = TAW\left[1 - e^{-\left\{\frac{ETM}{(1-p)SaD}\right\}}\right] \qquad (6)$$

where ETA and ETM are the fortnightly values of actual and maximum evapotranspiration in mm 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, (i) 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 (ii) a passive root zone below active root zone up to D_{max}. The time step of water balance is chosen as one fortnight. The soil water balance in the upper layer is governed by the fortnightly values of effective rainfall (Re_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 drainage out of this layer (DP) as deep percolation. The soil moisture content in the active layer ($SM1_{t+1}$) at the beginning of $(t+1)^{th}$ fortnight is estimated as

$$SM1_{t+1} = \frac{SM1_t D_t + Re_t + IW1_t + SM2_t (D_{t+1} - D_t) - P_t - ETA_t}{D_{t+1}} \quad (7)$$

$$P_t = Re_t + IW1_t - D_t\,(FC\text{-}SM1_t) \quad (8)$$
$$= 0.0 \text{ if } P_t < 0.0$$

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

$$SM2_{t+1} = SM2_t + \frac{P_t - DP_t}{D_{max} - D_t} \quad (9)$$

$$DP_t = P_t - (FC - SM2_t)(D_{max} - D_t)$$
$$= 0 \quad if \quad DP_t < 0 \quad (10)$$

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

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

$$Re = 0.8\,R - 25 \quad \text{if } R \geq 75 \text{ mm}$$
$$= 0.6\,R - 10 \quad \text{if } R < 75 \text{ mm} \quad (11)$$

A generic root growth model [Borg & Grimes (1986)] is used to calculate the root depth in mm as

$$D_T = D_{max}\left[0.5 + 0.5 Sin\left\{3.03\left(\frac{T}{T_{max}}\right) - 1.47\right\}\right] \quad (12)$$

where D_T is the root depth T days after planting in mm and D_{max} is the maximum depth of roots in mm 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 top 150 mm of the profile. T_{max} for all crops is taken as 85 days.

DP Formulation

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. In DP problem, intraseasonal time period 't' is taken as stage, soil moisture available in the active root zone ($SM1_t$) and irrigation water available (IW_t) at the beginning of intraseasonal period are considered as 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

$$Ry_t\left(SM1_t, IW1\right) = \left[1 - k_y\left(1 - \frac{ETA}{ETM}\right)\right] \quad (13)$$

Objective function of DDP is maximization of seasonal relative yield (Y_a/Y_m) and is given as

$$\text{Maximize} \prod_{t=1}^{nt} Ry_t\,(SM1_t, IW1) \quad (14)$$

Recursive equation of backward DP problem for any time period t can be written as

$$Ory_t\left(SM1_t, IW\right) =$$
$$Max\left[Ry_t\left(SM1_t, IW1\right) \times Ory_{t+1}\left\{SM1_{t+1}, \left(IW - IW1\right)\right\}\right]$$

for t = nt-1, nt-2 ,………1 (15)

and when t = nt,

$$Ory_{nt}\left(SM1_{nt}, IW\right) = Max\left\{Ry_{nt}\left(SM1_{nt}, IW1\right)\right\} \quad (16)$$

subject to

$$0 \leq IW1 \leq IW \leq IW_{max}$$

where Ory_t (SM1, IW) = maximum value of the objective function when SM1 is the soil moisture available at the beginning of time period 't' and IW is the water available for allocation for all time periods starting from last time period 'nt' to the current time period 't' and $SM1_{t+1}$ = soil moisture at the beginning of the $(t+1)^{th}$ period obtained from equations (7) and (8). IW_{max} is the maximum irrigation requirement.

Seasonal Crop Water Production Functions

Intraseasonal allocation model is used to determine 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 function of net seasonal irrigation water applied and is fitted into a 5^{th} degree polynomial function. Regression analysis by method of least squares is adopted to estimate the parameters and general form may be expressed as

$$\frac{Y_a}{Y_m} = \sum_{i=0}^{5} a_i w_i \qquad (17)$$

in which Y_a is yield of the crop when w is the net seasonal water applied , Y_m is maximum yield of the crop when there is no limitation of water and a_i is coefficient of i^{th} term of equation.

Annual Allocation Plan

Optimal annual irrigation planning model has been developed for the estimated annual available water to obtain area and water allocation for each crop of all seasons in a year grown under the command area of each main canal taking off from the reservoir. This model is developed using multi-level approach. At seasonal level, seasonal allocation policy is prepared in which seasonal reservoir release and area is allocated among the competing crops in the same season. At annual level, inter-seasonal allocation policy is developed after obtaining the seasonal allocation policy, to allocate annual available water and area of each command area under each main canal for two seasons of the year. At reservoir level, inter-canal allocation policy is developed to allocate annual available reservoir water among command areas of each canal taking off from the reservoir. Irrigation planning model is to run once in a year at the beginning of the first reservoir operation time to obtain optimal area and seasonal water allocations to each crop of each season of the year.

Allocation at Seasonal Level

At seasonal level, optimal policy of allocation of water and area among crops grown in each season under each main canal is obtained by dynamic programming using crop water production functions. Crop 'c' of Season 's' grown under canal 'i' represents the stage of the problem. 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.

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

$B(AC_{i,s,c}, RC_{i,s,c})$ is the benefit in million rupees of Indian currency from all crops of season 's' grown under canal 'i' taking off from the reservoir when $AC_{i,s,c}$ and $RC_{i,s,c}$ is the area and seasonal water applied to crop 'c' of season 's' and is calculated as

$$B(AC_{i,s,c}, RC_{i,s,c}) = (Y_{i,s,c}\, PC_{i,s,c}\, AC_{i,s,c} - PO_{i,s,c}\, A_{i,s,c} - P_w R_{i,s,c})\ 1.0e\text{-}06 \qquad (18)$$

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

Recursive equations of DP can be written as

$$TSB_{i,s,c}(SA, SR) = Max\left[Max\left\{B(AC, RC) + TSB_{i,s,c+1}(SA - AC, SR - RC)\right\}\right] \qquad (19)$$

for c=nc(i,s)-1, nc(i,s)-2,……….1

and when c=nc(i,s),

$$TSB_{i,s,,nc(i,s)}(SA,SR) = Max\ [Max\ \{B(AC, RC\}] \qquad (20)$$

subject to

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

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

$$SAMIN_s \leq \sum_{c=1}^{nc_s} AC_{i,s,c} \leq SAMAX_s$$

where $TSB_{i,s,c}(SA,SR)$ = Maximum Total benefit from all the crops starting from the last crop 'nc_s' to the current crop 'c' of season s grown under canal 'i' when AC and RC are the area and release allocated to crop 'c' of season 's' and SA and SR are the states of area and release available for allocation. AC_{max}, AC_{min}, RC_{max} and RC_{min} are the maximum and minimum limits of acreage and gross seasonal irrigation allocatable to crop respectively. $SAMAX_s$ and $SAMIN_s$ are the maximum and minimum limits of area for season 's'.

Allocation at Interseasonal Level

At interseasonal level, annual water available and area under each main canal of reservoir are to be allocated among the two seasons Kharif and Rabi maximizing total annual benefit from the command area of each main canal from the reservoir. The allocation problem is solved by DP technique. Season 's' represents the stage of the problem.

Objective function of the model is

$$Maximize \sum_{s=1}^{2} TSB_{i,s,1}(AS, RS)$$

where $TSB_{i,s,1}(AS,RS)$ = optimal benefit for season 's' obtained from seasonal allocation policy where AS and RS are the area and water allocated to each season of canal 'i'.

The recursive equation of the DP model can be written as

$$TAB_{i,s}\left(AA, RA\right) = Max\left[Max\left\{TSB_{i,s,1}\left(AS, RS\right) + TAB_{i,s+1}\left(AA - AS, RA - RS\right)\right\}\right] \quad (21)$$

for s = 1
and when s=2,

$$TAB_{i,2} = Max\ \{TSB_{i,2,1}(AS,RS)\} \quad (22)$$

Subject to

$0 \leq AS \leq AA \leq SAMAX_s$

$0 \leq RS \leq RA$

$$TA \leq \sum_{s=1}^{2} AS_s$$

$$TR \leq \sum_{s=1}^{2} RS_s$$

where $TAB_{i,s}$ (AA, RA) = Maximum benefit from two seasons Kharif and Rabi under canal 'i' when AA and RA are the states of area and water available at the beginning of the season 's' for allocation to two seasons . TA and TR are total annual area and release available to be allocated for two seasons of command area under canal 'i'.

Allocation at Reservoir Level

At reservoir level, the annual available water from the reservoir is to be allocated among command areas under two main canals taking off from the reservoir maximizing the total annual benefit from the project. Command area under each main canal 'i' is the stage of the DP problem.
Objective function of the DP problem is

$$Maximize \sum_{i=1}^{2} TAB_{i,1}(TA, TR)$$

Where $TAB_{i,1}$ = Maximum annual benefit from command area under main canal 'i'.
The recursive equation of the DP model can be written as

$$TPB_i\left(R\right) = Max\left[Max\left\{TAB_{i,1}\left(TA, R1\right) + TPB_{i+1}\left(TA, R - R1\right)\right\}\right] \quad (23)$$

for i=1 and when i=2,

$$TPB_2 = Max\ \{TAB_{i,1}(TA,R1)\} \quad (24)$$

where TPB_i (R) is the maximum benefit from all command areas of both main canals starting from last main canal 'nmc' to the current canal 'i' when R is the state of available release to be allocated for all canals starting from last canal to current canal 'i' and R1 is the release allocated to i[th] canal.

Results and Discussion

Mean monthly meteorological data of Khammam and Rentachintala IMD stations are collected to find reference evapotranspiration (ETo) of Nagarjuna Sagar Left Canal (NSLC) and Nagarjuna Sagar Right Canal (NSRC) respectively by Penman-Monteith equation. Table 1 present estimated ETo at Khammam and Rentachintala stations. Fortnightly crop evapotranspiration is obtained by multiplying crop coefficient of a fortnight with its corresponding fortnight reference evapotranspiration. Soil storage parameters viz., field capacity (FC) and permanent wilting point (PWP) are taken as 46% v/v and 21% v/v respectively [Rao (1998)]. 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 fortnights. 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. Fortnightly ETM of crops are estimated by multiplying ETo with the Kc values corresponding to the growth stage of crops.

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% v/v 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 mm to

Table 1. Reference Evapotranspiration ETo from model

Month	Khammam ETo (mm/day)	Rentachintala ETo (mm/day)
January	3.890	4.00
February	5.142	4.72
March	6.510	5.62
April	6.934	6.16
May	7.472	6.44
June	6.031	5.67
July	4.016	4.92
August	3.881	4.64
September	3.863	4.34
October	3.699	4.11
November	3.547	3.81
December	3.846	3.70

400 mm with an increment of 40 mm are considered as state variables in single crop intraseasonal allocation model. In case of rice, depth of standing water including soil water is considered as state variable and a pre-sowing depth of 200 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. 3 for crops grown under NSRC command.

Optimal irrigation planning strategies for

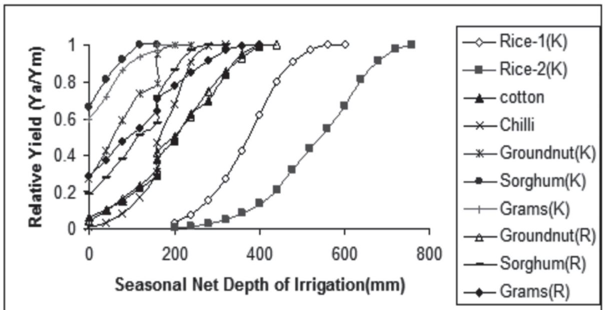

Fig. 3 Seasonal Water Production Functions of Crops under NSRC

Nagarjuna Sagar left canal and right canal command are developed. Allocations of area and water are made at seasonal, interseasonal and reservoir levels by deterministic dynamic programming (DDP), maximizing the net annual benefit from the project using optimal irrigation planning model. Optimal cropping pattern and irrigation water allocations are made with full and deficit irrigation strategies for various levels of probability of exceedences of expected annual water available.

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 2 & 3). The maximum area available for planting is 300,000 ha, 450,000 ha for Kharif season and the total maximum area available for both the seasons is 500,000 ha, 600,000 ha for NSLC and NSRC respectively. As rice is the principal food crop grown, constraint on minimum area is imposed to satisfy the local food requirements. Rice is irrigated by flooding method and other crops are irrigated by furrow method. The irrigation efficiency is taken as 56% in Kharif season and 42% for Rabi season. Agro economic parameters adopted in the study and the maximum net benefit that can be obtained for each crop are tabulated in

Table 2. Area and Irrigation constraints of NSLC command

Crop (Season)	Area (thousand ha)		Net irrigation (mm)	
	Max.	Min.	Max.	Min.
Rice-1 (K)	100	50	600	600
Rice-2 (K)	100	50	680	680
Cotton	10	—	320	—
Chilli	10	—	320	—
Groundnut (R)	40	—	440	—
Sorghum (R)	80	—	280	—
Grams (R)	80	—	400	—

Table 3. Area and Irrigation constraints of NSRC command

Crop (Season)	Area (thousand ha)		Net irrigation (mm)	
	Max.	Min.	Max.	Min.
Rice-1 (K)	110	50	760	760
Rice-2 (K)	110	50	800	800
Groundnut (K)	40	—	280	—
Sorghum (K)	80	—	160	—
Grams (K)	110	—	240	—
Cotton	110	—	440	—
Chilli	40	—	360	—
Groundnut (R)	40	—	480	—
Sorghum (R)	50	—	360	—
Grams (R)	80	—	440	—

Table 4. Price of water is considered as Rs.120, 000 per MCM.

Annual canal releases during the period 1967 - 2001 (35 years) are used for determining annual water availability. Skewness coefficient and kurtosis of series are calculated as -0.56 and 3.19 respectively. The expected values of annual water available for different probability of exceedences of 90%, 85%, 80% and 75% are 6800, 7200, 7500 and 8600 MCM respectively. 121 discrete values of state variable of area starting from 0 to 600,000 ha with an increment of 5,000 ha and 861 discrete values of state variable for available water starting from 0 to 8600 MCM with an increment of 10 MCM are considered.

Alternative strategies considered for planning purpose due to inadequacy of available water supplies to irrigate the entire available land are as follows.

Strategy-1: Restricting to full irrigation so that crop is not subjected to water stress resulting maximum yield per hectare but with limited area under irrigation.

Strategy-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. Table 5 presents annual allocation plan for the annual water availability corresponding to 75% PE.

From the results of irrigation planning model, it is evident that the total annual benefit and total allocated area is higher with strategy-2 when compared with strategy-1 for all levels of water availability. For all levels of water availability, area of commercial crops cotton and chilli is confined to their maximum limits for both strategies as the marginal net benefit per hectare is high. Low deficits of 2% for cotton and 5% for chilli is recommended, as the marginal net benefit per cubic meter of water applied is declining steeply with increase of percentage deficit irrigation. It may also be noted that maximum deficit is allocated to grams and sorghum in Kharif season for all levels of water availability as

Table 4. Agro Economic Parameters

Crop (Season)	Max. yield (kg/ha)	Market price (Rs./kg)	Cost of cultivation (Rs./ha)	Netbenefit (Rs./ha)
Rice (K)	5,400	5.65	10,900	18,045
Cotton	3,000	15.30	20,520	24,523
Chilli	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

Table 5. Area & Water allocation at 75% PE annual available water (8600 MCM)

		Area ('000 ha) and water ('000 MCM) allocated											
		Kharif season					Rabi season						
Strategy	Command	Rice-1	Rice-2	Groundnut	Sorghum	Grams	Cotton	Chilli	Groundnut	Sorghum	Grams	Total Area ('ooo ha.) (Total water '000 MCM)	Total Benefit in Million Rupees
1	NSLC	100 (1080)	100 (1220)	—	—	—	10 (60)	10 (60)	40 (420)	80 (540)	75 (720)	415 (4100)	6807.2
	NSRC	50 (680)	50 (720)	40 (200)	70 (200)	100 (430)	100 (790)	40 (260)	40 (460)	15 (130)	60 (630)	565 (4500)	9744.8
2	NSLC	100 (950)	100 (1120)	—	—	—	10 (50)	10 (50)	40 (390)	80 (470)	80 (610)	420 (3640)	6884.3
	NSRC	110 (1410)	60 (790)	40 (170)	0.0 (0.0)	100 (250)	100 (780)	40 (230)	40 (420)	30 (210)	800 (700)	600 (4960)	10647.0

yield response to water deficit is not much sensitive. Acreage of rice is restricted to the minimum imposed limit for both strategies in case of NSRC. 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 Conclusion

A model is developed for optimal irrigation planning and demonstrated through a case study. Crop water requirements are estimated from the evapotranspiration model. Crop water production functions are developed from single crop intraseasonal allocation model. Optimal allocations of land and water are made at seasonal, interseasonal and reservoir levels by running allocation model maximizing the annual net benefit from the project at different reliability levels of annual water availability and the results obtained are discussed. The study indicates that model presented can be used to determine the optimal water resources allocation, optimal planting area across various crops in a season and among various seasons in a year under each main canal taking off from the reservoir. As the problem is solved by decomposing into various levels (seasonal, intraseasonal and reservoir), the obstacles of dimensions are overcome. The model can be adopted in arid and semi-arid areas for better water management. 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. However, 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 DP problem. The randomness of rainfall occurrence, as well as amount and duration are not taken into account and 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 reservoir component and by updating the forecasted meteorological and hydrological input data.

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