Water Resources Management **16:** 145–169, 2002.

Optimal Crop Planning and Conjunctive Use of Water Resources in a Coastal River Basin

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(Received: 25 June 2001; accepted: 2 March 2002)

Abstract. Due to increasing trend of intensive rice cultivation in a coastal river basin, crop planning and groundwater management are imperative for the sustainable agriculture. For effective management, two models have been developed *viz.* groundwater balance model and optimum cropping and groundwater management model to determine optimum cropping pattern and groundwater allocation from private and government tubewells according to different soil types (saline and non-saline), type of agriculture (rainfed and irrigated) and seasons (monsoon and winter). A groundwater balance model has been developed considering mass balance approach. The components of the groundwater balance considered are recharge from rainfall, irrigated rice and non-rice fields, base flow from rivers and seepage flow from surface drains. In the second phase, a linear programming optimization model is developed for optimal cropping and groundwater management for maximizing the economic returns. The models developed were applied to a portion of coastal river basin in Orissa State, India and optimal cropping pattern for various scenarios of river flow and groundwater availability was obtained.

Key words: groundwater balance, linear programming, optimum cropping, salinity and permissible mining allowance, water resources management

1. Introduction

In view of the ever-increasing human population, intensive rice cultivation and non-availability of canal water in the coastal humid regions of eastern India, the groundwater resources are under high pressure of deterioration in quantity and quality. The deterioration of the groundwater quality is the result of intrusion of seawater into the aquifers due to lowering of fresh groundwater level caused by excessive groundwater abstraction. Due to increasing water scarcity, greater attention is being given to water management in irrigated as well as in rainfed agriculture. A farmer at the start of each irrigation season needs to have optimum cropping pattern and irrigation programs, which will maximize the economic return. Under these circumstances there is an urgent need to introduce efficient techniques in land

and water resources management for optimal utilization of the available land and water resources.

A number of simulation and optimization models have been applied in the past to decide planning and operating strategies for irrigation reservoir systems (Kumar and Pathak 1989; Vedula and Mujumdar, 1992). Rao *et al.*, (1990) developed a model for optimal weekly irrigation scheduling policy for two crops by considering both seasonal as well as intra seasonal competition for water. Vedula and Nagesh Kumar (1996) developed a mathematical programming model to determine the steady state optimal operating policy and the associated optimal crop-water allocations to all the crops for a single purpose irrigation reservoir, combining linear programming in the intraseasonal period and stochastic dynamic programming in inter seasonal period.

Most farming situations are concerned with several crops grown in the same season. Both allocations of land and water resources under a multi-crop situation in a season should be considered (Paul *et al.*, 2000). Paul *et al.*, (2000) developed optimal resources allocation strategies for a canal command in the semiarid region of India in a stochastic regime, considering the competition of crops in a season, both for irrigation water and area of cultivation.

The development of optimization models for improved water management expanded rapidly in the last decade. Linear programming is used for multiple crop models and dynamic programming for a single crop model. In irrigated agriculture, where various crops are competing for a limited quantity of land and water resources, linear programming is one of the best tools for optimal allocation of land and water resources (Smith, 1973; Maji and Heady, 1980; Loucks *et al.*, 1981; Yaron and Dinar, 1982: Pleban, *et al.*, 1983; Tyagi and Dhruva Narayana, 1984; Chavez-Morales, *et al.*, 1987; Loftis and Houghtalen 1987; Sritharan, *et al.*, 1988; Afshar and Marino, 1989; Mayya and Prasad, 1989; Paudyal and Gupta, 1990; Kaushal, *et al.*, 1985; Panda *et al.*, 1996; Sethi, 2001).

In recent years considerable attention has been given to problems associated with groundwater management and salinity control. Groundwater management has been studied from different view points, e.g., the economic control of groundwater management under institutional restrictions (Burt, 1970), the conjunctive management of groundwater and surface water (Cummings and Winkle, 1974, Khepar and Chaturvedi, 1982, Panda *et al.*, 1985) and groundwater management and salinity control (Cummings and Winkle, 1974, Hallaji and Yazicigil, 1996).

Water resources management is generally done by water balance for crop planning. In the present study the optimal cropping pattern and area allocation with respect to availability of water resources (both surface and groundwater) were obtained for different seasons by developing an optimization model. Water balance model has also been developed using the methods of Satish Chandra and Saxena (1975) and Panda *et al.* (1996) considering mass balance approach. In addition to the rational water use, there is need for selecting economically viable cropping pattern for a given area with available resources. Such cropping pattern can be obtained through the use of optimization models. The optimal cropping pattern was obtained for different soil types (saline and non-saline), type of agriculture (rainfed and irrigated) and seasons (monsoon and winter) using Linear Programming (LP) model. The objective of the LP model is to find the maximum annual net return from different cropping patterns and areas for all types of agriculture (rainfed and irrigated) under different soil types. This optimization is subject to various constraints such as surface and groundwater availability and their mass balance, cropping pattern restrictions. These models were applied to a portion of coastal river basin in Orissa State, India. The study was undertaken with a view to assist in taking decisions about crop planning and groundwater management.

2. Study Area

The study area, a portion of coastal river basin in India, is situated within the north latitude of 21°27′ 0″ to 21°45′ 45″ and east longitude of 86°56′ 15″ to 87°20′ 30″ spanning over an area of 1066 square kilometers, out of which 833.15 square kilometers is cultivable land (Figure 1). The area is situated in three administrative blocks, namely, Balasore Sadar, Basta and Baliapal of Balasore district in Orissa State, India.

The study area is bounded on the north and the south by two rivers (Subarnarekha and Budhabalang), on the east by Bay of Bengal and on the west by hilly areas of Mayurbhanj district of Orissa State. The area can be categorized into three distinct morphological units *viz.* saline marshy tract along the coast, the gently slopping alluvial plain in the central part and the hilly region in the western parts. The saline marshy tract forms a long and narrow strip along the coast. The width of this tract varies from 3 to 5 km and is intersected by a good number of tidal streams and is covered by shrubby vegetation. The gently sloping alluvial plain is situated to the west of the saline marshy tract and is the most fertile part of the area. The general slope of this tract is towards east and southeast and varies from 0.57 to 1.33 m per km. The hilly region in the western part is an extension of the Eastern Ghats mountain range. These hill ranges are trending roughly in the northeast-southwest direction. The maximum elevation in this region is 40 m above mean sea level. The climate of the area is characterized by tropical monsoon climate having three distinct seasons *viz.* monsoon, winter and summer. The average annual rainfall of the region varies between 1500–2000 mm, two third of which occurs in monsoon season between mid-June and mid-September. During this period, a large volume of rainwater from the rice fields discharges into the sea through surface drains and rivers. In this process, a huge quantity of fertile soil nutrients and applied fertilizers are drained into the sea. A study of the existing cultivation practices reveals that the farmers usually grow crops in two seasons (monsoon and winter) in both rainfed and irrigated areas. Farmers normally grow rice as a principal crop. Apart from rice, pulses, oilseeds and vegetables are the other crops grown during monsoon and winter seasons. In summer season there is no cultivation in

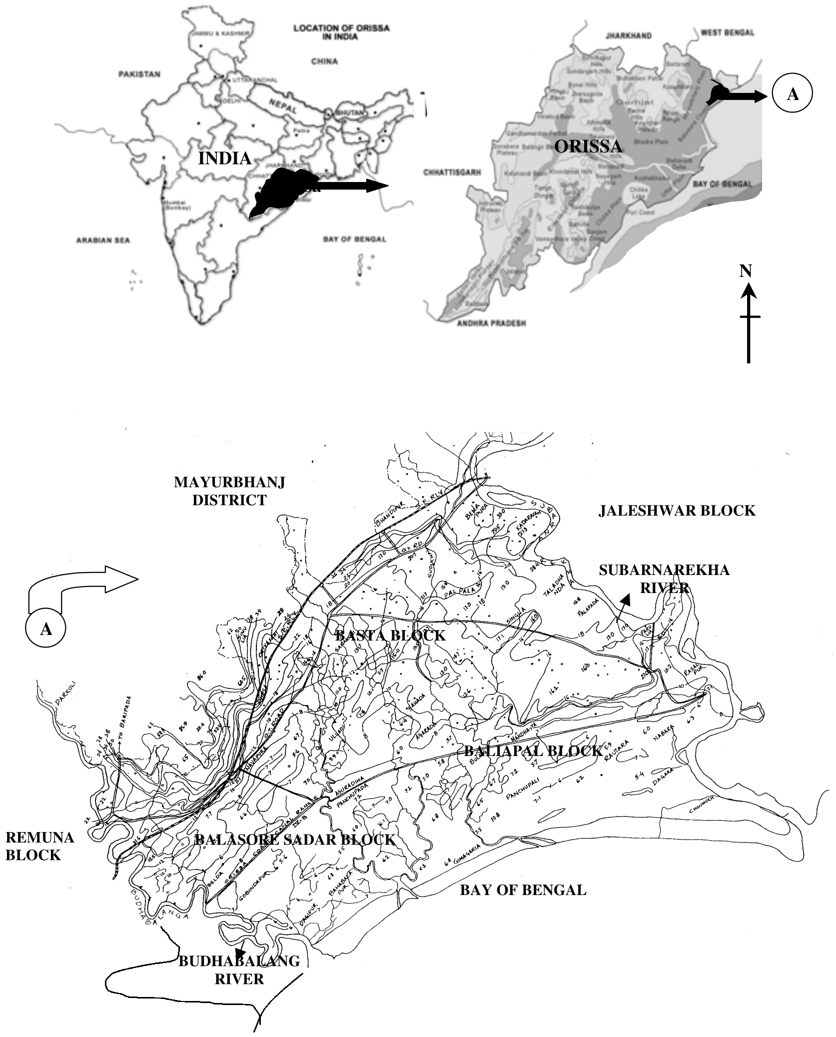

Figure 1. Location map of study area.

the area. In the various seasons the cropping area does not remain the same. This is due to the uncertainty of rainfall, scanty water resources, uncontrolled grazing of animals, management problems due to considerable distance from the farmers' houses, theft possibilities of high valued crops and other socio-economic problems. The only sources of water available for irrigation are the groundwater and the river water from Subarnarekha and Budhabalang. In the study area, no canal irrigation system is available. The structures used for irrigation are the government owned deep tubewells (more than 60 m) and private shallow (less than 20 m) and mini-deep tubewells (between 20 and 60 m) and river lifts. Cost of groundwater from government owned deep tubewells (here afterwards referred as government tubewells) is subsidized by the state government. Therefore, groundwater abstraction is intensive in the rice-cultivated areas. If the present increasing trend of groundwater abstraction continues, it may further lead to decline in groundwater table, seawater intrusion, and non-functioning of shallow tubewells operated by centrifugal pumps. So, a farmer at the start of each irrigation season needs to have optimum cropping pattern and irrigation program to maximize his economic returns.

3. Model Development

Two models, *viz.* groundwater balance model and optimum cropping and groundwater management model are developed to determine the optimum cropping pattern and groundwater allocation corresponding to different soil type (saline and non-saline), type of agriculture (rainfed and irrigated) and seasons (monsoon and winter).

3.1. GROUNDWATER BALANCE MODEL

Groundwater balance is an important aspect of any study on allocation of water resources, planning and management. The objective of the groundwater balance model is to regulate the groundwater flow system so as to prevent the water table from rising too close and/or declining too far from the root zone of the crops. This amounts to increasing or reducing the groundwater discharge at different locations as per requirement. The simplest form of groundwater balance equation is given by:

$$\Delta S = TGR_r - TGD_d \tag{1}$$

in which ΔS = change of groundwater storage, m^3; TGR_r = total groundwater recharge, m^3; and TGD_d = total groundwater draft, m^3.

3.1.1. *Groundwater Recharge*

Groundwater recharge consists of recharge from rainfall, seepage flow from surface drains, base flow from rivers, deep percolation from irrigated rice and non-rice areas. However, seepage from field drainage channels and conveyance system has been neglected. The annual groundwater recharge (starting of monsoon season to end of winter season) has been estimated by using the following equation:

$$TGR_r = R_r + GR_p + GR_{np} + BF + SF \tag{2}$$

in which R_r = recharge to the groundwater from rainfall, m^3; GR_p = recharge to the groundwater from irrigated rice area, m^3; GR_{np} = recharge to the groundwater from irrigated non-rice area, m^3; SF = seepage flow to the study area from drains, m^3; and BF = base flow to the area from the rivers, m^3.

Recharge from Rainfall

To compute the recharge from rainfall, ten years monthly rainfall data of the study area was collected from the Central Water Commission office, Balasore, Orissa. Annual groundwater recharge (cm) from rainfall in cm was calculated using the following equation given by Satish Chandra and Saxena (1975).

$$R_r = 3.984(\mathrm{R}_{av} - 40.64)^{0.5} \tag{3}$$

in which R_{av} = average annual rainfall of the area, cm.

Recharge from Irrigated Fields

Recharge from irrigated fields including losses in field channels was estimated using the norms recommended by the Groundwater Estimation Committee (1984) as follows. The different percentages of seepage and percolation in crop fields adopted are based on the studies conducted in similar areas

a) Recharge from irrigated rice area (GR_p): 35 to 64% of tubewell discharge
b) Recharge from irrigated non-rice area (GR_{np}): 30 to 36% of tubewell discharge

In the present study recharge from tubewells and from river lift irrigated fields (including losses in field channels) for rice and non-rice fields are taken as 55 and 30%, respectively.

Base Flow from Rivers

In the present study, the major groundwater recharge contribution is the base flow from Subarnarekha and Budhabalang rivers. Until recently, the common methods used for estimation of base flow are direct-measurement method, the curve tangent method, the basin area method and the chemical and isotope method (Delleur, 1998). In the present study, direct-measurement methodology has been used for estimation of the base flow from rivers, where an accurate estimate of hydraulic conductivity of the soils of the riverbeds was obtained using Falling Head Permeameter method in the laboratory. The Darcy's law was used to estimate the base flow from rivers considering the annual average groundwater flow gradient on both sides of the rivers and the cross-sectional area through which flow takes place.

Seepage Flow from Drains

Seepage from drains depends on factors like seepage rate, wetted perimeter, length of drains contributing to seepage and the number of days water remains in the drains. Due to unavailability of data related to estimation of the seepage from drains, it was computed considering run off available in drains as 40% of the total rainfall (Sarma *et al.*, 1983). Seepage flow from drains to groundwater was assumed as 8% of the total run off available in drains (Satish Chandra and Saxena, 1975).

Table I. Existing seasonal water resources systems and the extraction from the water resources

Name of sources	Structures	Number		Average discharge ($m^3\ s^{-1}$)	Operating hours ($h\ day^{-1}$)		Total draft (Mm^3)	
		Monsoon	Winter		Monsoon	Winter	Monsoon	Winter
Surface water	River lift	15	37	0.020	9	12	1.12	3.84
	Government tubewell	200(4)	507(4)	0.040	12	14	42.30	130.95
Groundwater	Private shallow tubewell	96	240	0.006	10	12	2.99	7.47
	Private mini-deep tubewell	107(45)	335(45)	0.025	12	12	19.70	51.62

Source: Lift Irrigation Corporation, Balasore, Orissa, India.
Note: Figures in the parenthesis indicate number of structures in saline area.

3.1.2. *Groundwater Discharge*

Groundwater discharge consists of draft from tubewells and evaporation from groundwater, which is given by:

$$TGD_d = GD_t + GD_e \tag{4}$$

in which GD_t = groundwater draft from tubewells, m^3; GD_e = evaporation from groundwater, m^3.

Groundwater Draft

Private shallow and mini-deep tubewells and government deep tubewells in the study area are being used for pumping the groundwater. The number of tubewells varies in different years. The year-wise groundwater draft is based on discharge, number of wells and duration of operation of wells in each season (Table I).

Evapotranspiration from Groundwater

Evapotranspiration from groundwater is difficult to be evaluated. In the study area the average groundwater level varies from 3 to 9 m below surface. The evapotranspiration from groundwater is assumed negligible due to high depth of water table from the surface and absence of deep-rooted forest plants.

3.2. OPTIMAL CROPPING AND GROUNDWATER MANAGEMENT MODEL

The objective of the model is to maximize the net annual return from the study area considering the returns from crop but excluding the irrigation cost. The decision variables of the models are seasonal area allocation to crops and surface water and groundwater application for crop production. The rainfall and irrigation requirement of crops, which are inputs to the model, are considered as stochastic variables.

3.2.1. *Objective Function*

The objective function consists of maximizing the net annual return (Z) from the coastal river basin subject to constraints on the availability of water and other inputs.

$$MaxZ = \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{c=1}^{n} a_{ijkc}A_{ijkc} - \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \left[C_{ijk}^{RW}RW_{ijk} + (1+L_r)\left(C_{ijk}^{GW^P}GW_{ijk}^{P} + C_{ijk}^{GW^G}GW_{ijk}^{G}\right)\right] \quad (5)$$

in which i = soil type, i = 1 for coastal saline soil and i = 2 for inland non-saline soil; f = type of agriculture, j = 1 for rainfed agriculture and j = 2 for irrigated agriculture; k = crop growing season, k = 1 for monsoon season, and = k = 2 for the winter season; c = 1,2..., n; n = number of crops; a_{ijkc} = net return (excluding the cost of irrigation water) for crop c grown in season k of j^{th} type of agriculture in soil type i (Rs ha^{-1}) (US \$1 ≈ Indian Rupees, Rs. 48); A_{ijkc} = area allocated to crop c grown in season of k of j^{th} type of agriculture in soil type i (ha); C_{ijk}^{RW} = cost of lifting river water (RW) in season k for j^{th} type of agriculture in soil type i (Rs ha-m^{-1}); RW_{ijk} = river water allocated in season k for j^{th} type of agriculture in soil type i (ha-m); $C_{ijk}^{GW^P}$ = cost of groundwater from private tube well (P) in season k for j^{th} type of agriculture and in soil type i (Rs ha-m^{-1}); GW_{ijk}^{P} = groundwater pumped from private tube wells in season k for j^{th} type of agriculture in soil type i (ha-m); $C_{ijk}^{GW^G}$ = cost of groundwater from government tube well (G) in season k for j^{th} type of agriculture and in soil type i (Rs ha-m^{-1}); GW_{ijk}^{G} = groundwater pumped from government tube well in season k for j^{th} type of agriculture in soil type i (ha-m); and L_r = leaching requirement (fraction).

3.2.2. *Constraints*

Maximization of the objective function is subject to the following constraints.

1. *Water Allocation Constraint*

The expected irrigation requirements of all the crops must be fully satisfied during all the seasons from the available surface and groundwater resources and rainfall for both rainfed and irrigated agriculture of the coastal saline and non saline soil areas.

$$\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{c=1}^{n} NIR_{ijkc}A_{ijkc} - \sum_{i=1}^{2}\sum_{j=1}^{2}\alpha_1(\beta_1 RW_{ijk} + GW_{ijk}^{P} + GW_{ijk}^{G}) \leq 0 \quad \text{for all } k; \tag{6}$$

in which NIR_{ijkc} = net irrigation requirement of crop c, grown in season k for j^{th} type of agriculture in soil type i (m); α_1 = (1-θ_2) = field water application efficiency (fraction); θ_2 = field water application loss (fraction); β_1 = (1-θ_1) = conveyance efficiency of river lift system (fraction); and θ_1 = conveyance loss of river lift system (fraction);

2. *Land Area Constraint*
Land allocated to various crops during the monsoon and winter seasons must not exceed the available cultivable area for all types of agriculture and the soil types.

$$\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{c=1}^{n} A_{ijkc} \leq TA_k \qquad \text{for all } k \tag{7}$$

in which TA_k = total land area available in season k (ha);

3. *Water Availability Constraints*
The availability of water for irrigation from the surface water source is limited. So allocation of surface water must not exceed the available surface water during a season. Similarly for groundwater resources, tube well water allocation must not exceed the availability of groundwater during the season for the corresponding type of agriculture and also the type of soil.

(a) River Water

$$\sum_{i=1}^{2}\sum_{j=1}^{2} RW_{ijk} \leq ARW_k \qquad \text{for all } k \tag{8}$$

(b) Groundwater

$$\sum_{i=1}^{2}\sum_{j=1}^{2}(1+L_r)(GW_{ijk}^{P} + GW_{ijk}^{G}) \leq AGW_k \quad \text{for all } k \tag{9}$$

in which ARW_k = total available river water in season k after allowing for losses (ha-m); and AGW_k = total available groundwater in season k after allowing for losses (ha-m).

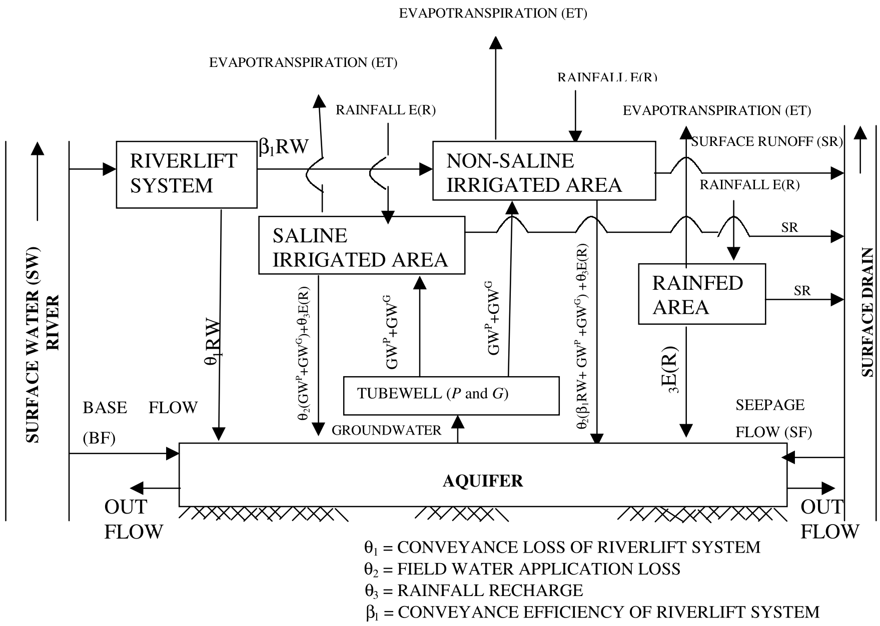

Figure 2. Flow chart of groundwater balance for the study area.

4. *Hydrologic Balance of aquifer*

The proper hydrologic balance of groundwater aquifer will help in keeping the water table at balanced position. Thus a hydrologic balance constraint should be satisfied (Figure 2).

Neglecting run-off, seepage from field drainage channels and evaporation losses and rainfall contribution to the water delivery systems during conveyance, the following expression is obtained.

$$\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\Big[\big(GW_{ijk}^{P}+GW_{ijk}^{G}\big)-\big\{\theta_1 RW_{ijk}+\theta_3 E(R)A_{ijk}+$$

$$\theta_2(\beta_1 RW_{ijk}+GW_{ijk}^{P}+GW_{ijk}^{G})\big\}-BF-SF\Big]\le PMA \qquad (10)$$

By rearranging

$$\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\big[(1-\theta_2)(GW_{ijk}^{P}+GW_{ijk}^{G})-(\theta_1+\theta_2\beta_1)RW_{ijk}\big]\le$$

$$\big[PMA+BF+SF+\theta_3 E(R)A_{ijk}\big] \qquad (11)$$

in which θ_3 = rainfall recharge (fraction); $E(R)$ = expected annual rainfall (m); *SF* = seepage loss to the study area from the drain (ha-m); *BF* = seepage loss to the study area from the river (ha-m); *PMA* = permissible annual mining allowance of the aquifer (ha-m); and *A* = cultivable area under considerations (ha).
Permissible annual mining allowance is determined as follows:

$$PMA = \Delta h \times A \times Y \quad (12)$$

in which Δh = permissible annual average groundwater table fluctuations (m); and Y = specific yield of aquifer (fraction).

5. *Minimum/Maximum Allowable Area*
Management considerations restrict some minimum and/or maximum value for irrigated areas under certain crops to meet the local food requirement.
a) For Maximum area

$$A_{ijkc} \leq \mu_{ijkc}^{\max} TA_{ijkc} \quad (13\text{-a})$$

b) For Minimum area

$$A_{ijkc} \geq \mu_{ijkc}^{\min} TA_{ijkc} \quad (13\text{-b})$$

in which $\mu_{ijkc}^{\max}$ = factor by which existing area of crop c can be increased in season k for j^{th} type of agriculture and soil type i; $\mu_{ijkc}^{\min}$ = factor by which existing area of crop c can be decreased in season k for j^{th} type of agriculture and soil type i and TA_{ijkc} = area of crop c as per existing pattern in season k for j^{th} type of agriculture and soil type i (ha).

6. *Non-negativity*

$$A_{ijkc} \geq 0;\ RW_{ijk} \geq 0;\ GW_{ijk}^{P} \geq 0;\ \text{and}\ GW_{ijk}^{G} \geq 0 \text{ for all } i, j, k, \text{ and } c \quad (14\text{a-d})$$

4. Estimation of Model Inputs

The model inputs include determination of the water resources data, leaching fraction, net irrigation requirement of crops at different probability of exceedances, net return of crops and permissible mining allowance.

4.1. WATER RESOURCES

In the study area, the sources of water available for irrigation purpose are river water and groundwater. Although the river water is of good quality, it falls short of the irrigation requirement of the area adjoining the river due to very few river lift-pumping units installed by government. The average electrical conductivity of the groundwater is 3.75 dS m^{-1} (deci Siemen/meter) in the saline area. The structures used for irrigation are the river lifts and government owned tubewells and private (shallow and mini deep) tubewells. The river water is supplied through 37 river lift irrigation schemes in the study area, which are programmed for different seasons (monsoon and winter) and soil type (saline and non-saline) according to demand. Details of river lift and groundwater pumping sources are given in Table I.

4.2. LEACHING REQUIREMENT

The upper aquifer of coastal saline area is of poor quality not suitable for irrigation whereas deeper aquifer is suitable for all purposes due to which all the mini-deep and deep tubewells are installed in the said layer. The leaching requirement (L_r) can be calculated based upon the electrical conductivity of irrigation water in salt affected areas (EC_{iw}) and threshold value of the electrical conductivity of irrigation water (EC_{th}) for crop tolerance as follows:

$$Lr = \frac{EC_{iw}}{EC_{th}} \tag{15}$$

in which EC_{iw} = electrical conductivity of irrigation water (dS m^{-1}); and EC_{th} = threshold electrical conductivity of water draining from the root zone (dS m^{-1}).

4.3. IRRIGATION REQUIREMENT OF CROPS

Crops grown in study area during monsoon season are rice (Oryza *sativa*), maize (*Zea mays*), sweet potato (Ipomoea *batatas*) and pigeon pea (*Cajanus cajan*) whereas winter season crops are rice, wheat (*Triticum aestivum*), groundnut (*Arachis hypogaea*), mustard (*Brassica juncea*), black gram (*Phaseolus mungo*), green gram (*Phaseolus aureus*), onion (*Allium cepa*), and garlic (*Allium sativum).*

Various methods are available to estimate the reference crop evapotranspiration (ET_o) (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998). Based on the availability of meteorological data of the study area, the Hargreaves and Samani (1985) method of estimating ET_o was selected as given below:

$$ET_o = 0.0135 R_{sl} (T_{\text{mean}} + 17.8) \tag{16}$$

in which ET_o = reference evapotranspiration in a given period (month) (mm/month); R_{sl} = incoming short-wave solar radiation in the considered period (mm/month); T_{mean} = mean temperature ($T_{\max}$ + $T_{\min}$)/2; $T_{\max}$ = monthly maximum air temperature (○C); $T_{\min}$ = monthly minimum air temperature (○C).

$$R_{sl} = 0.16 R_a (T_{\max} - T_{\min})^{0.5} \tag{17}$$

in which R_a = extra terrestrial solar radiation (mm/month).

Now, the crop evapotranspiration (ET_c) is calculated using the following equation,

$$ET_c = k_c ET_o \tag{18}$$

where, k_c = crop coefficient.

The crop coefficient (k_c) values for each crop were obtained from literature (Doorenbos and Pruitt, 1977 and Allen *et al.*, 1998). The U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) method (Dastane, 1977) was used to determine the effective rainfall. The total depth of net irrigation requirement of crop that needs to be applied to meet the crop demand can be estimated from the following equation:

$$NIR = ET_c - E_R \tag{19}$$

in which *NIR* = net irrigation requirement in a given month, mm/month; and E_R = effective rainfall in the given month, mm/month;

The seasonal net irrigation requirement (*NIR*) of crops has been computed by adding the monthly *NIR* of crops corresponding to the months in the growing season.

4.4. PROBABILITY OF EXCEEDANCE (PE)

The daily rainfall and temperature of the study area for 10 yr (1991–2000) was collected and converted to monthly values. These values were used to predict the expected monthly rainfall and evapotranspiration at different probability levels. The values were entered in the database of SMADA package (Statistical Model for Analysis of Distribution function) considering Weibull's distribution as reference and fitted to different probability functions. From the best-fit distribution (in this case, normal distribution), the value of the monthly-expected reference evapotranspiration at 10, 20, 30, 40, 50, 60, 70, 80, and 90% probability levels could be obtained. Based on these values, the net irrigation requirements (*NIR*) of crops at various probability levels of exceedance (PE) were computed for both the growing seasons, and are shown in Figures 3 and 4 for monsoon season and winter season respectively. The optimal annual returns at different probability levels of NIR and the optimal groundwater allocation are computed by assuming that all the components of the groundwater balance taken in the calculations are correct.

4.5. NET RETURNS OF CROPS

The net return from the cultivation of selected crops per unit area of farming was calculated by considering the potential yield from the crops. The variation of net return excluding irrigation water cost depends upon the type of soil, agriculture and the crops with their corresponding yield, market price and the cost of cultivation.

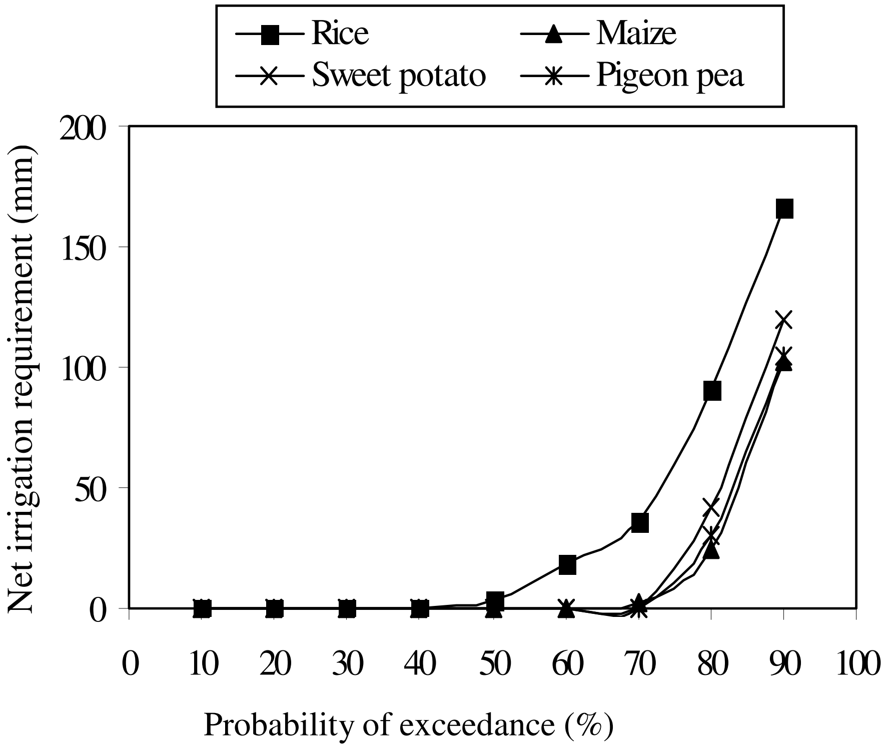

Figure 3. Variation of net irrigation requirement of crops with different probability of exceedance level during monsoon season.

The potential yield values of the study area were collected from the Agriculture Department, Government of Orissa. The cost of production of various crops excluding the cost of irrigation water was obtained from the budget for monsoon and winter crops suggested by the Department of Statistics and Economics, Orissa, India. The net returns excluding the irrigation water cost for crop c, season k, agriculture type j and soil type i were determined based on these inputs (Table II).

4.6. PERMISSIBLE MINING ALLOWANCE

Permissible mining allowance (safe yield) is the upper limit of groundwater pumping without creating adverse effect on groundwater management. Adverse effect may be either declining or rising of groundwater table or intrusion of poor quality water either from sea (salt water intrusion) or from adjoining aquifer due to creation of adverse flow gradients. The groundwater should be managed so that the average depletion does not exceed the permissible mining allowance. The permissible mining allowance (*PMA*) is calculated using Equation 12.

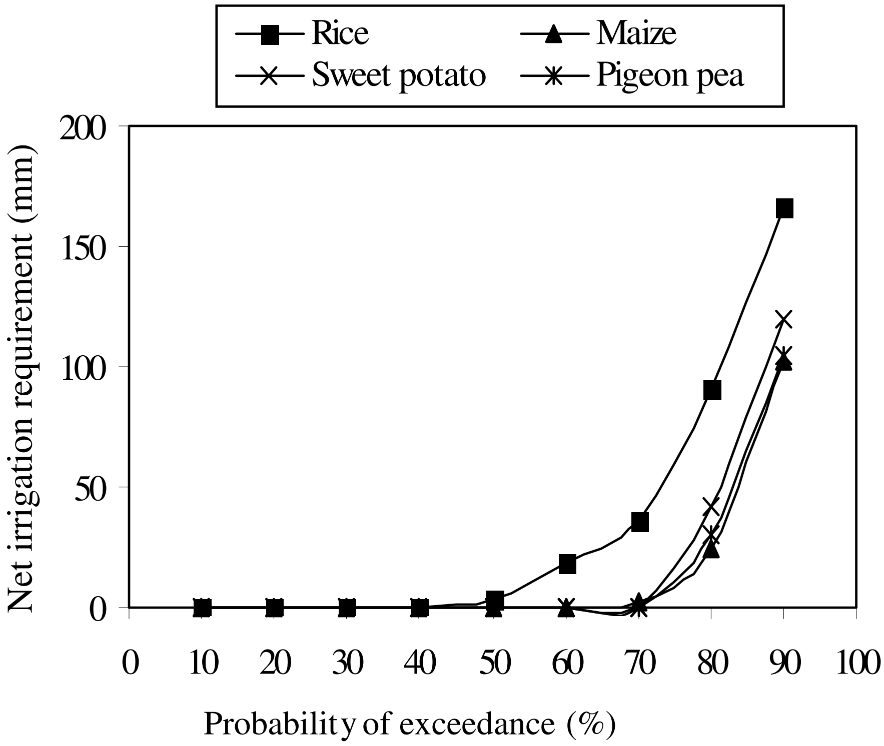

Figure 4. Variation of net irrigation requirement at different probability of exceedance level during winter season.

5. Model Application

The coastal river basin is divided into the saline and non-saline areas based on the geography and the salinity of the soil. The total cultivable area (TA_{ijkc}) for saline when i = 1 and non-saline when i = 2 are 60 and 773.15 sq. Km, respectively. The cultivable area is categorized into rainfed and irrigated according to the type of agriculture. Finally the cropping pattern was decided based on the cultivation season, soil and agriculture type. The existing cropping pattern and corresponding net returns excluding the irrigation water cost for crop *c*, season *k*, agriculture type *j* and soil type *i* of the study area are shown in Table II. The unit cost of irrigation water supply through the government owned riverlifts (C_{ijk}^{RW}) and tubewells pumping units ($C_{ijk}^{GW^G}$) is Rs. 1,715.55/ha-m^{-1} and for privately owned shallow and mini-deep tubewells ($C_{ijk}^{GW^P}$) is Rs. 3,333.30 ha-m^{-1}. The supplies of river water during monsoon and winter seasons (ARW_k) are 43.55 and 653.18 Mm^3, respectively. Water samples from all the tubewells were analyzed. The electrical conductivity of groundwater varied from 0.60 to 1.42 dS m^{-1}, with an average of 1.00 dS m^{-1} in non-saline area and 3 to 4.5 dS m^{-1} with an average of 3.75 dS m^{-1} in saline area. For most of crop in the study area salinity tolerance is 6 dS m^{-1}. The

Table II. Existing cropping pattern and net return excluding irrigation cost

Soil Type (i)	Agriculture (j)	Seasons k)	Crops (c)	Area (ha) A_{ijkc}	Yield (1000 kg ha^{-1})	Cost of cultivation (Rs[a] ha^{-1})	Net return (excluding irrigation cost) (Rs[a] ha^{-1}) a_{ijkc}
Saline	Rainfed	Monsoon	Rice	3,700	1.9	10,000	1,830
			Maize	750	1.0	4,750	1,250
	Irrigated	Monsoon	Rice	1,400	2.1	11,000	2,110
			Maize	150	1.2	5,150	2,050
		Winter	Rice	1,500	2.4	11,000	4,000
Non-Saline	Rainfed	Monsoon	Rice	64,765	3.0	10,000	9,140
			Maize	215	1.1	4,750	1,850
			Pigeon pea	225	0.8	5,700	14,300
		Winter	Mustard	285	0.8	5,550	12,050
			Groundnut	325	1.2	9,050	8,950
			Black gram	584	0.8	4,290	7,710
			Green gram	492	0.8	4,290	7,710
	Irrigated	Monsoon	Rice	11,521	3.5	12,000	10,250
			Maize	180	1.4	4,750	3,650
			Sweet potato	264	0.8	5,570	23,514
			Pigeon pea	95	1.0	6,700	18,300
		Winter	Rice	21,198	4.0	12,000	13,360
			Wheat	788	2.5	13,000	3,850
			Maize	623	1.5	5,150	3,850
			Mustard	2,847	1.2	5,550	20,850
			Groundnut	4,100	2.0	9,050	20,950
			Black gram	2,023	1.5	4,550	13,450
			Green gram	2,947	1.5	4,550	13,450
			Garlic	389	1.0	2,000	4,000
			Onion	1,094	5.0	5,000	10,000

Source: District Agriculture Office, Balasore, Orissa, India.
[a] US \$1 ≈ Rs. 48.

leaching requirement (L_r) of the saline area was found to be 0.625, whereas for the non-saline area it is zero.

Water balance components were computed using the methods described earlier and norms, which are based on field experiments. The results show the recharge from different components of water balance, drafts from the groundwater struc-

Table III. Annual groundwater balance obtained from the groundwater balance model

Items	Million m^3
Inflow to the groundwater basin	
Recharge from rainfall	258.49
Recharge from river lifts and tube-wells irrigated rice area	85.15
Recharge from river lifts and tube-wells irrigated non-rice area	41.29
Base flow from Subarnarekha and Budhabalang rivers	508.78
Seepage from drains	43.25
Total inflow to the ground water basin	936.96
Evaporation from ground water	Negligible
Seepage to rivers and drains from groundwater as sub-surface out flow	Negligible
Ground water available	936.96
Usable groundwater (70% of available)	655.87
Groundwater draft from tube wells	255.03
Net groundwater resources to be developed	**400.84**

tures, the usable water resources and the net groundwater resources to be tapped for further development.

The total annual average groundwater recharge of the study area have been computed as 936.96 Mm^3 (million cubic meters) which includes annual recharge from rainfall $[\theta_3 E(R) A_{ijk}]$ as 258.49 Mm^3, base flow from rivers (*BF*) as 508.78 Mm^3, seepage flow from surface drains (*SF*) as 43.25 Mm^3, and discharge as 255.03 Mm^3 (Table III). The annual groundwater available (AGW_k) is 655.87 Mm^3. The permissible mining allowance (*PMA*) was found as 231.795 Mm^3. The conveyance loss of river lift system (θ_1) and field water application loss (θ_2) assumed is 0.2 and 0.3 (fraction), respectively (Panda *et al.*, 1996 and Sethi, 2001).

6. Optimum Resources Allocation

Optimization model (Linear programming) developed for optimum cropping pattern and groundwater management consisted of 35 decision variables out of which 25 variables correspond to crop variables and 10 correspond to water resources. The optimization model was run for nine different probability levels of exceedance (10, 20, 30, 40, 50, 60, 70, 80 and 90) of net irrigation requirements using QSB package (Chang, 1993). The model was also run for three different cropping situations *viz.*, Case 1: Without Area Constraints i.e. there are no lower and upper bounds on the area cultivated for each crop (in this case $\mu_{ijkc}^{\min} = 0$ and $\mu_{ijkc}^{\max} = 1$ for all *i, j, k* and *c*) Case 2: With rice area constraints i.e. rice cultivation is restricted to existing rice area while there are no bounds on all other crops. This alternative

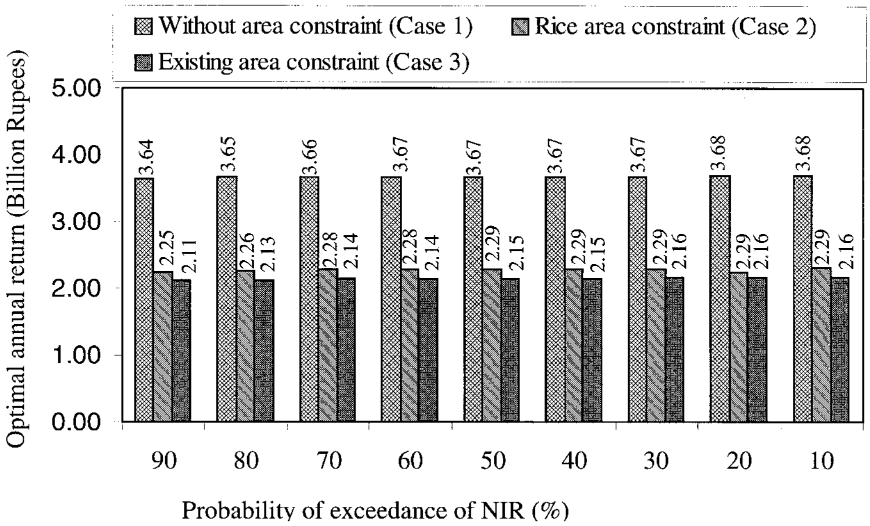

Figure 5. Optimal annual return with different probability of exceedance of NIR.

was examined since rice cultivation is essential for the farmers of the area for their food requirement even if it is not economical. Case 3: Existing cropping pattern. The optimal annual return obtained for different net irrigation requirements (NIR) corresponding to different probability levels of excedance is shown in Figure 5. Groundwater allocations from government tubewell for all the three cases at different levels of exceedance of NIR are shown in Table IV. As can be seen from Figure 5 and Table IV, there is very little variation in optimal annual return and groundwater allocation obtained for different NIR corresponding to different probability levels of exceedance. Therefore for further analysis, net irrigation requirements corresponding to 90% probability of exceedance is only considered.

The cropping pattern obtained from the optimum cropping and groundwater management model for the above three different cropping situations (case 1, 2 and 3) is presented in Table V considering NIR at 90% exceedance probability. For case 1, the crops with most economic benefit are preferred for cultivation in the entire area. They are sweet potato in monsoon season and groundnut in winter season. Although these may yield maximum annual return it may not be feasible due to the local food requirements. The results obtained for case 2, when a constraint is imposed for a minimum rice area as per the existing cropping pattern, are also shown in Table V. Annual return for the existing cropping pattern (case 3) is also shown in the same table.

No data is available from the study area regarding the minimum requirements of crops for the farmers as well as the food targets of the region. So, the model was run at three different ranges of the cultivable area considering the existing cropping pattern.

Table IV. Optimum groundwater allocation at different probability levels of exceedance of NIR corresponding to different cases of cropping situation

Probability level of exceedance	Groundwater allocation through government tubewell (Thousand ha-m)					
	Case 1		Case 2		Case 3	
	Monsoon	Winter	Monsoon	Winter	Monsoon	Winter
90	14.28	22.260	19.750	25.690	19.710	25.760
80	4.998	21.889	10.700	25.369	10.659	25.376
70	0	20.947	4.069	24.514	4.074	24.486
60	0	19.757	2.092	23.389	2.092	23.334
50	0	18.567	0.233	22.296	0.232	22.255
40	0	17.258	0	21.084	0	21.069
30	0	15.829	0	19.753	0	19.759
20	0	14.045	0	18.032	0	18.065
10	0	11.426	0	15.577	0	15.667

These ranges are (1) Allowing 20% deviation from the existing area for each crop i.e. $\mu_{ijkc}^{\min} = 0.8$ and $\mu_{ijkc}^{\max} = 1.2$ for all *i, j k* and *c*. (2) Allowing 40% deviation from the existing area for each crop i.e. $\mu_{ijkc}^{\min} = 0.4$ and $\mu_{ijkc}^{\max} = 1.6$ for all *i, j k* and *c*. (3) Allowing 50% deviation from the existing area for each crop i.e. $\mu_{ijkc}^{\min} = 0.5$ and $\mu_{ijkc}^{\max} = 1.5$ for all *i, j, k* and *c*. It may be noted that the total cropped area is restricted to the total cultivable area (Equation 7) in the model. Fifty percent of the existing cropped area is considered as the minimum required area to be cultivated for each crop. Therefore, deviations below 50% are not considered. Optimal cropping pattern obtained for the above three different ranges of the cultivable area with reference to existing cropping pattern are shown in Table V. It can be observed from the table that with the increase in allowable deviation from the existing cropping pattern more economic benefit is obtained. These alternative cropping patterns may be adopted as per the desire of the farmers to change their cropping pattern.

The optimum cropping and ground water management model was also run varying the surface and ground water availability at different levels (10% intervals) considering the existing potential fully utilized. The cropping pattern, water resources allocation with maximum annual net return obtained with varying surface and groundwater availability are presented in Tables VI and VII, respectively. Optimum annual return obtained for different levels of surface and groundwater availability are also shown in the tables.

Table V. Optimum area and groundwater allocation corresponding to three cropping situations and deviation ranges from the existing cropping pattern

Soil type	Agriculture	Season	Crop	Optimal area allocation (ha)						
				Symbol	Case 1	Case 2	Case 3	Range of the cultivable area corresponding to existing area		
				(A_{ijkc})				Range 1	Range 2	Range 3
Saline	Rainfed	Monsoon	Rice	A1	0.0	3700.0	3700.0	2960.0	2220.0	1850.0
			Maize	A2	0.0	0.0	750.0	600.0	450.0	375.0
	Irrigated	Monsoon	Rice	A3	0.0	1400.0	1400.0	1120.0	840.0	700.0
			Maize	A4	0.0	0.0	150.0	120.0	90.0	75.0
		Winter	Rice	A5	0.0	1500.0	1500.0	1800.0	2100.0	2250.0
Non-Saline	Rainfed	Monsoon	Rice	A6	0.0	64765.0	64765.0	63673.0	62531.0	61960.0
			Maize	A7	0.0	0.0	215.0	172.0	129.0	107.5
			Pigeon pea	A8	0.0	0.0	225.0	270.0	315.0	337.5
		Winter	Mustard	A9	0.0	0.0	285.0	342.0	399.0	427.5
			Groundnut	A10	0.0	0.0	325.0	390.0	455.0	487.5
			Black gram	A11	0.0	0.0	584.0	700.8	817.6	876.0
			Green gram	A12	0.0	0.0	492.0	590.4	688.8	738.0
	Irrigated	Monsoon	Rice	A13	0.0	11521.0	11521.0	13825.2	16129.4	17281.5
			Maize	A14	0.0	0.0	180.0	144.0	108.0	90.0
			Sweet Potato	A15	83315.0	1929.0	315.0	316.8	369.6	396.0
			Pigeon pea	A16	0.0	0.0	95.0	114.0	133.0	142.5
		Winter	Rice	A17	0.0	21198.0	21198.0	25437.6	29677.2	31797.0
			Wheat	A18	0.0	0.0	788.0	945.6	1103.2	1182.0
			Maize	A19	0.0	0.0	623.0	747.6	872.2	934.5
			Mustard	A20	0.0	0.0	2847.0	3416.4	3985.8	4270.5
			Groundnut	A21	83315.0	60617.0	48220.0	4920.0	5740.0	6150.0
			Black gram	A22	0.0	0.0	2023.0	2427.6	2832.2	3034.5
			Green gram	A23	0.0	0.0	2947.0	3536.4	4125.8	4420.5
			Garlic	A24	0.0	0.0	389.0	466.8	544.6	583.5
			Onion	A25	0.0	0.0	1094	1312.8	1531.6	1641.0
Optimal annual return (Billion Rupees)					**3.64**	**2.25**	**2.11**	**1.32**	**1.44**	**1.49**
Groundwater allocation			**Monsoon season**		**14.280**	**19.750**	**19.710**	**19.687**	**19.694**	**19.698**
(Thousand ha-m)			**Winter season**		**22.260**	**25.690**	**25.760**	**16.770**	**19.550**	**20.950**

7. Summary and Conclusions

Groundwater balance model has been developed using mass balance approach to estimate usable quantity of groundwater in the study area. Different components considered in this model are recharge from rainfall, irrigated rice fields, irrigated non-rice fields, base flow from rivers and seepage flow from drains.

The linear programming model for optimization of annual return was formulated for optimum water allocation and cropping pattern considering the saline and non-saline soil type, rainfed and irrigated agriculture and the monsoon and winter season and different crops. Following specific conclusions can be drawn for the study area based on the results obtained from the models.

- The water balance model shows that the additional water resources available (400.84 Mm^3) (after withdrawing 255.03 Mm^3) for further use is more than the present demand due to more recharge from rainfall (258.49 Mm^3) and base flow from rivers (508.78 Mm^3).
- The optimum cropping and groundwater management linear programming model yielded the cropping pattern for three situations. The optimal annual returns at 90% probability levels of NIR corresponding to three different cropping situation (Case 1, Case 2 and Case 3) are 3.64, 2.25 and 2.11 billion Rupees, respectively and the optimal value increases with decreasing probability levels of NIR.
- The optimal groundwater allocation for three different cropping situations attains the maximum level at 90% probability level of NIR and decreases with decreasing probability levels of exceedance of NIR.
- The model when imposed with a constraint of 20% of existing surface and groundwater supply level, yielded the allocation towards all resources (river and groundwater) for both the growing seasons.
- The cropping pattern obtained for three different ranges of deviation from the existing area for each crop also gives significant output in the form of alternative cropping pattern.

8. Conclusions

The groundwater balance of a basin was studied considering recharge from rainfall, irrigated rice fields, irrigated non-rice fields, base flow from rivers and seepage flow from drains and drafts through different groundwater structures like government deep tube wells, private shallow and mini deep tube wells. The linear programming model formulated for maximization of annual net return with optimal water and cropping pattern allocation considering the saline and non-saline soil type, rainfed and irrigated agriculture and the monsoon and winter seasons and the crops is found to be an effective tool for land and water resources allocation. State agencies and farmers involved in the actual agricultural production processes are advised to practise conjunctive use of river water and groundwater so as to restrict further depletion of groundwater level. However, the result of this study was mainly affected

Table VI. Optimum cropping (ha) and water allocation with varying river water supply

Crop	GW = 0.1, RW = 0.1; GW = 0.1, RW = 0.2; GW = 0.1, RW = 0.3; GW = 0.1; RW = 0.4; GW = 0.1, RW = 0.5		GW = 0.1; RW = 0.6	GW = 0.1; RW = 0.7	GW = 0.1; RW = 0.8	GW = 0.1; RW = 0.9	GW = 0.1; RW = full
A 1	**Infeasible**		2,200.0	2,200.0	2,200.0	2,200.0	2,200.0
A 2			450.0	450.0	450.0	450.0	450.0
A 3			840.0	840.0	840.0	840.0	840.0
A 4			90.0	90.0	90.0	90.0	90.0
A 5			900.0	2,100.0	2,100.0	2,100.0	900.0
A 6			62,531.0	62,531.0	62,531.0	62,531.0	62,531.0
A 7			129.0	129.0	129.0	129.0	129.0
A 8			315.0	315.0	315.0	315.0	315.0
A 9			171.0	399.0	399.0	399.0	171.0
A 10			195.0	455.0	455.0	455.0	195.0
A 11			350.4	817.6	817.6	817.6	350.4
A 12			295.2	688.8	688.8	688.8	295.2
A 13			16,129.4	16,129.4	16,129.4	16,129.4	16,129.4
A 14			108.0	108.0	108.0	108.0	108.0
A 15			369.6	369.6	369.6	369.6	369.6
A 16			133.0	133.0	133.0	133.0	133.0
A 17			12,718.8	29,677.2	29,677.2	29,677.2	12,718.8
A 18			472.8	1,103.2	1,103.2	1,103.2	472.8
A 19			373.8	872.2	872.2	872.2	373.8
A 20			2,781.3	3,985.8	3,985.8	3,985.8	2,781.3
A 21			2,460.0	2,630.4	3,934.5	5,238.5	5,740.0
A 22			1,213.8	1,213.8	1,213.8	1,213.8	2,052.2
A 23			1,768.2	1,768.2	1,768.2	1,768.2	1,768.2
A 24			233.4	233.4	233.4	233.4	233.4
A 25			656.4	656.4	656.4	656.4	656.4
River water allocation (Thousand ha-m)		**Monsoon season**	—	—	—	—	—
		Winter season	**2.61**	**3.05**	**3.48**	**3.9**	**4.354**
Groundwater allocation (Thousand ha-m)		**Monsoon season**	**6.558**	**6.558**	**6.558**	**6.558**	**6.558**
		Winter season	**19.694**	**19.694**	**19.694**	**19.694**	**19.694**
Optimal annual return (Billion Rupees)			**1.047**	**1.074**	**1.110**	**1.126**	**1.146**

Table VII. Optimum cropping pattern (ha) and water allocation with varying groundwater supply

Crop		RW = full; GW = 0 and RW = 0.2; GW = 0.1	RW = 0.2; GW = 0.2	RW = 0.2; GW = 0.3	RW = 0.2; GW = 0.4	RW = 0.2; GW = 0.5	RW = 0.2; GW = 0.6	RW = 0.2; GW = 0.7	RW = 0.2; GW = 0.8	RW = 0.2; GW = 0.9	RW = 0.2; GW = 1.0
A 1		**Infeasible**	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0
A 2			450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0
A 3			840.0	840.0	840.0	840.0	840.0	840.0	840.0	840.0	840.0
A 4			90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
A 5			900.0	2,100.0	2,100.0	2,100.0	2,100.0	2,100.0	2,100.0	2,100.0	2,100.0
A 6			57,563.0	62,531.0	62,531.0	62,531.0	62,531.0	62,531.0	62,531.0	62,531.0	62,531.0
A 7			129.0	129.0	129.0	129.0	129.0	129.0	129.0	129.0	129.0
A 8			315.0	315.0	315.0	315.0	315.0	315.0	315.0	315.0	315.0
A 9			171.0	399.0	399.0	399.0	399.0	399.0	399.0	399.0	399.0
A 10			455.0	455.0	455.0	455.0	455.0	455.0	455.0	455.0	455.0
A 11			350.4	817.6	817.6	817.6	817.6	817.6	817.6	817.6	817.6
A 12			295.2	688.8	688.8	688.8	688.8	688.8	688.8	688.8	688.8
A 13			16,129.4	16,129.4	16,129.4	16,129.4	16,129.4	16,129.4	16,129.4	16,129.4	16,129.4
A 14			108.0	108.0	108.0	108.0	108.0	108.0	108.0	108.0	108.0
A 15			369.6	369.6	369.6	369.6	369.6	369.6	369.6	369.6	369.6
A 16			133.0	133.0	133.0	133.0	133.0	133.0	133.0	133.0	133.0
A 17			19,070.6	29,677.2	29,677.2	29,677.2	29,677.2	29,677.2	29,677.2	29,677.2	29,677.2
A 18			472.8	1,103.2	1,103.2	1,103.2	1,103.2	1,103.2	1,103.2	1,103.2	1,103.2
A 19			373.8	872.2	872.2	872.2	872.2	872.2	872.2	872.2	872.2
A 20			3,985.8	3,985.8	3,985.8	3,985.8	3,985.8	3,985.8	3,985.8	3,985.8	3,985.8
A 21			5,740.0	5,740.0	5,740.0	5,740.0	5,740.0	5,740.0	5,740.0	5,740.0	5,740.0
A 22			2,832.2	2,832.2	2,832.2	2,832.2	2,832.2	2,832.2	2,832.2	2,832.2	2,832.2
A 23			4,125.8	4,125.8	4,125.8	4,125.8	4,125.8	4,125.8	4,125.8	4,125.8	4,125.8
A 24			233.4	544.6	544.6	544.6	544.6	544.6	544.6	544.6	544.6
A 25			1,531.6	1,531.6	1,531.6	1,531.6	1,531.6	1,531.6	1,531.6	1,531.6	1,531.6
River water	**Monsoon season**		**0.871**	—	—	—	—	—	—	—	—
(Thousand ha-m)	**Winter season**		**13.065**	**9.511**	**4.476**	—	—	—	—	—	—
Groundwater	**Monsoon season**		**13.12**	**12.09**	**16.113**	**19.694**	**19.694**	**19.694**	**19.694**	**19.694**	**19.694**
(Thousand ha-m)	**Winter season**		**8.056**	**19.551**	**19.551**	**19.551**	**19.551**	**19.551**	**19.551**	**19.551**	**19.551**
Optimal annual return (Billion Rupees)			**1.216**	**1.417**	**1.427**	**1.435**	**1.435**	**1.435**	**1.435**	**1.435**	**1.435**

by the variation in groundwater pumping, size of the pumping plant, unit cost of water, market price of the crops and cost of production.

Acknowledgements

The authors with to sincerely thanks to the Orissa Lift Irrigation Corporation Office at Jaleshwar and Balasore, District Agriculture Office at Balasore, Central Water Commission Office at Balasore for providing all necessary data. The financial support received from the Volkswagen Foundation, Germany for carrying out the investigation is also gratefully acknowledged.

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