Simulation-Optimization Modeling for Efficient Groundwater Management in a Deltaic Aquifer of Eastern India

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ABSTRACT

Numerical methods like simulation modelling and optimization play a vital role in the management of complex groundwater systems. The present study demonstrates the combined use of groundwater-flow and resource optimization models to scientifically address the water scarcity problem in Kathajodi-Surua Inter-basin within Mahanadi deltaic system of eastern India. The study area is rich in groundwater resources and has abundant water supply in the monsoon season. But there is water shortage in the post-monsoon season and groundwater supply is not sufficient to meet the entire water demand of the farmers. In order to meet irrigation requirement of different post-monsoon season crops to a maximum extent, a transient simulation-optimization model was developed using response-matrix technique to maximize the pumping from the tubewells. The total monthly maximum allowable groundwater withdrawals from the river basin were estimated at 1.63, 1.68, 1.60, 1.45, 1.60, 1.47 and 1.52 million m^3 in the months of November, December, January, February, March, April and May, respectively. The optimized maximum pumping rates obtained from the simulation-optimization model were used in a linear programming-based optimization model to determine optimal cropping pattern for wet, normal and dry scenarios. The net annual income from the optimal cropping patterns for the wet, normal and dry scenarios were estimated at Rs. 81.83 million, Rs. 76.36 million and Rs. 71.55 million, respectively. The results of simulation-optimization modeling revealed that if the suggested optimal cropping patterns are adopted in the study area, the net annual irrigation water requirements will be reduced by 28 to 40%, and net annual income will be increased by 17 to 28%.

1. INTRODUCTION

The growing urbanization, increasing population, agriculture expansion, rapid industrialization and economic development in India has resulted in increase in water demand in all the sectors (Kumar et al., 2005; Mall et al., 2006). Roughly 52% of irrigation consumption across the country is extracted from groundwater, and there are several parts of the country that face water scarcity due to intensive groundwater exploitation (CGWB, 2006) and mismanagement. Excessive groundwater exploitation has led to alarming decrease in groundwater levels in several parts of the country such as Tamil Nadu, Gujarat, Rajasthan, Odisha, West Bengal, Punjab and Haryana (Sharma and Gupta, 1999; Mall et al., 2006; CGWB, 2006). In recent studies, the analysis of GRACE satellite data revealed that the groundwater reserves in the states of Rajasthan, Punjab and Haryana are being depleted at a rate of 17.7 ± 4.5 km^3/yr (Rodell et al., 2009). Thus, the depletion of groundwater resources has increased the cost of pumping, caused seawater intrusion in coastal areas and has raised questions about sustainable groundwater supply as well as environmental sustainability.

The state of Odisha in eastern India is no exception and it has its own share of water problem with diverse situation in different parts like the recurrence of drought in western parts, pockets of saline water in the coastal tract and acute water scarcity in many other parts. Because of uneven nature of rainfall and its capricious distribution, there is an increasing dependence on groundwater resources for meeting the growing water demand of agriculture, industrial and domestic sectors. Even though sufficient water is available in coastal areas in the monsoon season, there is a water shortage for irrigation in the post-monsoon season. Therefore, there is a need to develop optimal groundwater management strategies to increase area under post-monsoon season crops and thereby sustain agricultural productivity and livelihoods.

Numerical techniques are required to best satisfy the competing water demands in a basin. Simulation models in conjunction with optimization models constitute a powerful set of tools for maximizing utilization of available land and water resources, and for providing cost-effective management goals. In the last four decades, groundwater simulation models and groundwater simulation-optimization models have been widely used for developing optimal groundwater management strategies in different parts of the world. However, in developing countries like India, basin-wide groundwater modeling studies are still in its initial stage due to several socio-scientific factors such as the lack of adequate and good-quality field data, financial resources, infrastructure, and proper technical expertise. As a result, so far very few studies on basin-wide groundwater-flow modeling (Ahmed and Umar, 2009; Raul et al., 2011) and groundwater simulation-cum-optimization modeling (Garg and Ali, 2000; Rejani et al., 2009) have been carried out in India in general and eastern India in particular. The present study was conceived for demonstrating the efficacy of combined groundwater-flow simulation and resource optimization models in developing efficient strategies for the sustainable management of groundwater in deltaic aquifers. To achieve this objective, a study area, Kathajodi-Surua Inter-basin, located in the Odisha state of eastern India was selected. The present study is first of its kind in the study area.

2. STUDY AREA

The study area, Kathajodi-Surua Inter-basin, (locally known as Bayalish Mouza) is a typical river island within the Mahanadi deltaic system of Odisha, eastern India and is surrounded on both sides by the Kathajodi River and its branch Surua (Fig.1). The total geographical area of the study area is 35 km^2 and agriculture is the major occupation of the inhabitants. Groundwater is the only source of irrigation in the study area. There are 69 functioning government tubewells in the area, which constitute major sources of groundwater withdrawals for irrigation. These tubewells were constructed and managed by the Odisha Lift Irrigation Corporation, Government of Odisha, India. Now, they have been handed over to the local water users' associations. As such, there is no water shortage during the monsoon Season in the study area, but in the latter part of post-monsoon season, the farm ponds and dug wells dry up and groundwater levels start lowering. As a result, water scarcity prevails in the study area during the dry season and it threatens the sustainability of agricultural production and livelihoods. This situation warrants that water management strategies should be evolved using modern tools and techniques for sustainable management of water resources in the study area.

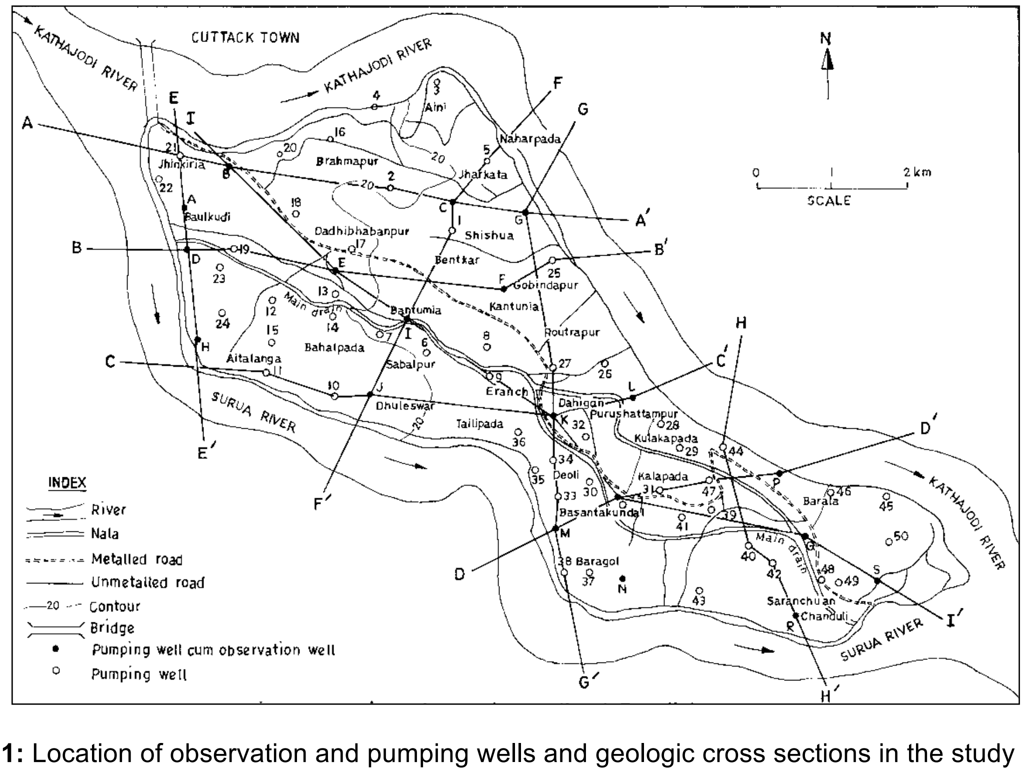

Fig. 1: Location of observation and pumping wells and geologic cross sections in the study area.

3. MATERIALS AND METHODS

3.1 Data Collection and Analysis

Daily rainfall data of 20 years (1990-2009) and daily pan evaporation data of 4 years (2004-2007) were collected from a nearby meteorological observatory at Central Rice Research Institute (CRRI), Cuttack, Odisha located at about 2 km from the study area. The 20 years rainfall data were analyzed for investigating annual and monthly variations of rainfall of the study area. The frequency analysis of the monthly rainfall data was performed using SMADA 6.0 software. The best-fit probability distribution function was determined based on Chi-square error. Using the best-fit probability distribution functions for different months, the probabilities of monthly rainfalls at 20%, 50% and 80% exceedence of rainfall were found out. Based on the regional experience, they are represented as monthly rainfall under wet, normal and dry scenarios, respectively.

The lithologic data at 70 sites over the study area were collected from Odisha Lift Irrigation Corporation (OLIC) Office, Cuttack, Odisha. The lithologic data were analyzed in detail, which along with other field data were used for developing numerical groundwater-flow model of the study area. Since no groundwater data were available in the study area, a groundwater monitoring program was initiated by the authors. Monitoring of groundwater levels in the study area was done by selecting nineteen tubewells in such a way that they represent approximately four west-east and four north-south cross-sections of the study area (Fig. 1). Weekly groundwater-level data at the nineteen sites was monitored from February 2004 to October 2007, which was used for studying the groundwater characteristics in the study area and calibration of groundwater-flow simulation model.

3.2 Calculation of Crop Water Requirement

The irrigation requirement of the crops in the study area is mostly in the post-monsoon (Rabi) season. Paddy, sugarcane, potato, onion, groundnut, vegetables, greengram, blackgram, horsegram and mustard are major crops in the study area during this season. The Department of Agriculture, Government of Odisha has fixed target areas of coverage under these Rabi crops. The targeted areas are 710 ha, 130 ha, 200 ha, 20 ha, 82 ha, 400 ha, 165 ha, 201 ha, 320 ha 150 ha and 36 ha for paddy, sugarcane, potato, onion, groundnut, winter vegetables, summer vegetables, greengram, blackgram, horsegram and mustard respectively. The water requirements of these crops (i.e., ET_c) were determined by the pan evaporation method (Allen et al., 1998).

3.3 Development of Simulation-Optimization Model

3.3.1 Groundwater-flow simulation model

A groundwater-flow simulation model of the study area was developed using Visual MODFLOW software for analyzing groundwater condition in the study area. The model was developed following the modeling protocol suggested by Anderson and Woessner (1992). This included the development of a conceptual model of the study area based on the lithology and other field data, descretization of the basin and design of numerical model, assignment of initial and boundary conditions and estimation of model parameters. The eastern boundary of the study area is bounded by the Kathajodi River and the western boundary is bounded by the Surua River (Fig. 1). Therefore, these boundaries were simulated as Cauchy boundary conditions. The developed model was calibrated using weekly groundwater-level data of February 2004 to May 2006 at 19 sites. A combination of trial-and-error technique and automated calibration code PEST was used to calibrate the developed numerical model considering hydraulic conductivity, specific storage and recharge as calibration parameters. Thereafter, the calibrated model was validated using weekly groundwater-level data of June 2006 to May 2007. The statistical indicators as well as the comparison of observed and simulated groundwater levels showed a reasonably good calibration and validation of the groundwater-flow simulation model. The calibrated values of hydraulic conductivity varied from 20 to 52 m/day, while that of specific storage varied from 4.3×10^{-6} to 2.75×10^{-5}.

3.3.2 Generation of response matrices

The calibrated flow-simulation model was used to develop a transient response matrix. Transient response functions describe the influence of a unit pulse of pumpage on drawdown over space and time (Halaji and Yazicigil, 1996). A transient response function in the discrete form is given as (Maddock, 1972):

$$s_{kn} = \sum_{i=1}^{NPW} \sum_{j=1}^{n} \beta(k,i,n-j+1)\ q_{ij} \qquad \ldots (1)$$

Where S_{kn} = drawdown at site k at the end of total pumping period n (m), β(k,i,n-j+1) = average drawdown at site k at the end of pumping period n due to a unit pulse of pumpage at the i^{th} well during j^{th} pumping period (s/m^2), q_{ij} = average discharge at the i^{th} well during j^{th} pumping period (m^3/s), i = index for the number of wells, j = index for the time period (months), k = index for the site number, n = total number of time periods, and NPW = total number of pumping wells.

A planning horizon of 7 months (November to May) corresponding to the post-monsoon irrigation season in the region with a monthly time step was considered for the development of simulation-optimization model. Consequently, transient response functions $\beta_{ki(n-j+1)}$ were generated from repeated runs of the flow-simulation model for a period of 7 months by successively subjecting each of the pumping wells to a unit discharge for the first one month period and zero discharge for the rest of the six months. Drawdowns at 69 pumping wells were simulated by pumping of the wells over the 7-month pumping period. The response functions so obtained (a total of 33327) were then assembled to form a transient response matrix. The response-function approach is usually applicable to a linear system, i.e., confined aquifer system (Hallaji and Yazicigil, 1996). Since the Kathajodi-Surua Inter-basin comprises confined aquifer, the use of this approach in this study is justified.

3.3.3 Formulation of transient hydraulic management model

A transient hydraulic management model was developed to maximize pumping from the basin by integrating the transient response matrix generated from groundwater flow simulation model with the non-linear optimization model. The objective function of the model was to maximize the total pumpage from the basin. That is,

$$Max\ Q = \sum_{i=1}^{69} \sum_{j=1}^{7} q_{ij} d_j \qquad \ldots (2)$$

Where Q = total pumpage from the existing wells (m^3); q_{ij} = pumpage of the i^{th} well in the j^{th} month (m^3/sec); d_j = number of days of pumping in the j^{th} month; i = index for well number; and j = index for time period (j = 1 to 7; 1 for November; 2 for December and so on). While applying Eqn. (2), it was assumed that the pumps are operated for maximum 12 hours a day.

The above objective function was subjected to the following three constraints:

(1) Drawdown constraint:

At the pumping wells, the drawdown must not exceed the maximum permissible drawdown for all time steps. Using the transient response functions, this constraint can be expressed as follows (Maddock, 1972):

$$\sum_{i=1}^{69} \sum_{j=1}^{7} \beta(k,i,n-j+1)\ q_{ij} \le S_k^{\max},\ k = 1, 2, 3.....69 \qquad \ldots (3)$$

Where, β (k, i, n-j+1) = average drawdown at the k^{th} site due to a unit pulse of pumpage at the i^{th} well during j^{th} month; n = total number of time periods; k = index for site number; $S_k^{\max}$ = maximum allowable drawdown at the k^{th} site (m).

(2) Water demand constraint:

The total groundwater demand of the crops in each month must be satisfied. That is,

$$\sum_{i=1}^{69} q_{ij} d_j \ge D_j \quad j = 1, 2....7 \qquad \ldots (4)$$

Where, D_j = water demand of the crops in the j^{th} month (m^3); d_j = number of days of pumping in the j^{th} month.

(3) Pumping capacity constraints:
The pumping in individual wells can not exceed the pumping capacity of the wells and it has to be a positive value. That is,

$$0 \le q_{ij} \le q_{ij}^{\max}, \quad i = 1, 2, 3.....69;\ j = 1, 2...7 \qquad \text{... (5)}$$

Where, $q_{ij}^{\max}$ = maximum pumping capacity of the i^{th} well in j^{th} month.

The above optimization model was solved using the LINGO 8.0 software package.

Inputs of the model
The inputs of the hydraulic management model are the monthly water demand of the crops, drawdown coefficients, maximum permissible drawdown at 69 well sites, and maximum rate of pumping of wells.

3.4 Optimization Model for Land and Water Resources Management

With the available land and water resources, a linear programming optimization model was formulated to determine optimal cropping pattern in the study area by maximizing the net annual return subject to various land and water related constraints. The model was developed to suitably allocate 11 crops, viz., paddy, sugarcane, potato, onion, groundnut, winter vegetables, summer vegetables, greengram, blackgram, horsegram and mustard in different land types, i.e., high land, medium land and low land so that net annual return can be maximized.. The optimization model was developed for the wet, normal and dry scenarios, respectively.

3.4.1 Formulation of optimization model
The objective function of the optimization model was to maximize the net annual return in wet, normal and dry scenarios, which is expressed as follows:

$$Max\ Z = \sum_{i=1}^{3}\sum_{j=1}^{11}(P_jY_j - C_j - I_{ij})a_{ij} \qquad \text{... (6)}$$

Where, Z = net total annual income corresponding to wet, normal and dry scenarios (Rs.); P_j = market price of the j^{th} crop (Rs./kg); Y_j = yield of the j^{th} crop (kg/ha); C_j = cost of cultivation per unit area for the j^{th} crop excluding the cost of irrigation water (Rs./ha); I_{ij} = irrigation cost for the j^{th} crop in the i^{th} type of land (Rs./ha); a_{ij} = area under the j^{th} crop in the i^{th} type of land (ha); i = index for land type (1 for high land, 2 for medium land, and 3 for low land); and j = index for crop type (1, 2, 3,…,11).

The objective function was subjected to the following sets of constraints.

(1) Land availability constraint
Land allocated to various crops must not exceed the total available land under each category (high land, medium land and low land). That is,

$$\sum_{j=1}^{11} a_{ij} \le A_i; \quad i = 1, 2, 3 \qquad \text{... (7)}$$

Where, a_{ij} = area under the j^{th} crop in the i^{th} type of land, and A_i = total area of the i^{th} type of land (i =1 for high land, i = 2 for medium land and i = 3 for low land).

(2) Water requirement constraint
The net irrigation requirement of all the crops grown in the study area in all the months must satisfy the available maximum groundwater withdrawals for all the pumping wells in a particular month.

$$\sum_{i=1}^{3}\sum_{j=1}^{11} a_{ijk}.w_{ijk} \le W_k; \quad k = 1, 2,...., 7 \qquad \text{... (8)}$$

Where a_{ijk} = area under the j^{th} crop in the i^{th} type of land in the k^{th} month, w_{ijk} = water requirement of the j^{th} crop in the i^{th} type of land in the k^{th} month, W_k = available irrigation water (i.e., maximum groundwater withdrawals) in the k^{th} month (k =1 for January, k = 2 for February,….., and k = 7 for May). The available irrigation water W_k in different months is obtained by the following equation:

$$W_k = \eta \sum_{i=1}^{69} q_{ik} d_k; \quad k = 1, 2, \ldots, 7 \qquad \ldots (9)$$

Where, η = irrigation efficiency, q_{ik} = maximum allowable pumpage of the i^{th} well in the k^{th} month (m^3/sec); d_k = number of days of pumping in the k^{th} month (k = 1 for January, k = 2 for February,…….., and k = 7 for May).

(3) Minimum/Maximum area constraint
Management considerations restrict some maximum and minimum areas under each crop to meet the basic food requirement of the area. This constraint is expressed as:

$$A_j^L \le \sum_{i=1}^{3} a_{ij} \le A_j^U; \quad j = 1, 2, 3, \ldots 11. \qquad \ldots (10)$$

Where, A_j^L = minimum area under the j^{th} crop, and A_j^U = maximum area under the j^{th} crop.
The above optimization model was also solved using the LINGO 8.0 software package.

3.4.2 Inputs of the optimization model
Inputs of the optimization model includes total area under high land, medium land and low land, maximum and minimum areas under different crops, water requirement of crops in different months in different land types and net income from crops in different land types. The net incomes from the crops were computed from the potential crop yields, price of the crops, cost of cultivation, and irrigation cost. In addition, the maximum permissible pumping rates of each well were obtained from the developed hydraulic management model and served as an input to the optimization model. The areas under high land, medium land and low land are 956 ha, 1081 ha and 408 ha, respectively. An irrigation efficiency of 90% was considered in this study because only groundwater is used in the study area for irrigation.

4. RESULTS AND DISCUSSION

4.1 Crop Water Requirement

The net irrigation requirements of paddy in the wet, normal and dry scenarios were found as 875.2, 938.2 and 999.2 mm, respectively. The total crop water requirements in the months of November, December, January, February, March, April and May were estimated at 4.76×10^5, 9.01×10^5 , 26.47×10^5, 22.65×10^5, 24.69×10^5, 22.16×10^5 and 8.13×10^5 m^3, respectively. Similarly, the total water requirements for the rabi paddy, sugarcane, potato, onion, groundnut, winter vegetables, summer vegetables, greengram, blackgram, horsegram and mustard were determined as 73.85×10^5, 7.47×10^5, 5.78×10^5, 0.59×10^5, 2.21×10^5, 10.65×10^5, 5.03×10^5, 3.27×10^5, 5.24×10^5, 3.0×10^5 and 0.8×10^5 m^3, respectively.

4.2 Maximum Permissible Groundwater Withdrawal

The value of maximum permissible pumpage was highest in the months of November and December, thereafter gradually reduced to a minimum in the months of April and May. From the month-wise maximum permissible pumping rates in the 69 tubewells, the total monthly maximum allowable pumpage from the river basin were estimated at 1.63, 1.68, 1.60, 1.45, 1.60, 1.47 and 1.52 million m^3 in the months of November, December, January, February, March, April and May, respectively. It should be noted that the actual pumping from a well in each month will depend on the cropping pattern followed by the farmers. Therefore, it is essential to determine optimal cropping pattern and optimal pumping schedule for the study area.

4.3 Optimal Cropping Pattern and Groundwater Allocation

The optimal allocation of different crops to different land types, the optimal allocation of groundwater to different crops and the net annual income from the optimal cropping patterns in different scenarios is presented in Table 1. The crops such as sugarcane, potato, onion, winter vegetables and summer vegetables have been allotted the maximum area possible in all the three scenarios, because their net incomes are higher. Greengram crop has also been allotted maximum area possible in all the three scenarios, whereas groundnut crop is allotted maximum area possible only in wet and normal scenarios. On the other hand, the area under paddy crop has been limited to 304 ha in the wet scenario and a minimum area of 177 ha in the normal and dry scenarios. It should be noted that even though paddy has a higher net income than the crops like groundnut and greengram, its area has been limited due to the higher water requirement. All the areas under low land (408 ha), medium land (1081 ha) and high land (956 ha) are covered under crops in the wet scenario, whereas in the normal and dry scenarios, only entire low land and medium land were covered under crops. The cropped area under high land in the normal scenario and dry scenario were 747 ha and 327 ha respectively, which can be attributed to the relative shortage of irrigation water during these two scenarios.

Table 1: Optimal cropping pattern, net irrigation requirement and net annual income in different scenarios

Crop	Wet scenario		Normal scenario		Dry Scenario	
	Allotted land (ha)	Net Irrigation Requirement (m^3)	Allotted land (ha)	Net Irrigation Requirement (m^3)	Allotted land (ha)	Net Irrigation Requirement (m^3)
Paddy	304 (all in low land)	24.64×10^5	177 (all in low land)	16.01×10^5	177 (all in low land)	17.41×10^5
Sugarcane	195 (all in med. land	5.72×10^5	195 (all in med. land)	8.71×10^5	195 (all in med. land)	10.19×10^5
Potato	300 (all in high land)	6.41×10^5	300 (all in high land)	7.77×10^5	300 (62 in med. land and 238 in high land)	8.28×10^5
Onion	30 (all in high land)	0.65×10^5	30 (all in high land)	0.79×10^5	30 (all in med. land)	0.84×10^5
Groundnut	123 (all in high land)	2.40×10^5	123 (all in high land)	2.95×10^5	52 (all in high land)	1.33×10^5
Winter Vegetables	600 (104 in low land and 496 in med. land)	9.35×10^5	600 (231 in low land and 369 in med. land)	12.72×10^5	600 (222 in low land and 378 in med. land)	14.60×10^5
Summer Vegetables	248 (all in high land)	2.92×10^5	248 (all in high land)	5.40×10^5	248 (all in high land)	6.72×10^5
Greengram	315 (all in high land)	3.20×10^5	315 (all in high land)	3.96×10^5	315 (all in med. land)	4.53×10^5
Blackgram	480 (336 in med. land and 144 in high land)	4.78×10^5	285 (193 in med. land and 92 in high land)	3.85×10^5	101 (all in med. land)	1.53×10^5
Horsegram	44 (all in high land)	0.58×10^5	202 (all in high land)	3.47×10^5	37 (all in high land)	0.69×10^5
Mustard	54 (all in med. land)	0.74×10^5	9 (all in med. land)	0.16×10^5	9 (all in low land)	0.18×10^5
Total	2693	61.40×10^5	2484	65.78×10^5	2064	66.30×10^5
	Net Annual Income = Rs. 81.83×10^6		Net Annual Income = Rs. 76.36×10^6		Net Annual Income = Rs.71.55×10^6	

It is worth mentioning that the optimization model suggests total cropped areas of 2693 ha, 2484 ha and 2064 ha in wet, normal and dry scenarios, respectively as compared to the total cropped area of 2423 ha targeted by the Department of Agriculture, Government of Odisha in the study area. Thus, based on the optimal cropping patterns, there is a reduction of 75% in the area under paddy and an increase of 50% in the area under sugarcane, potato, onion, winter vegetables, summer vegetables and greengram in the post-monsoon season. As the paddy cultivation consumes a lot of water and its net income is not so high, it is strongly recommended to reduce the area under post-monsoon paddy so as to conserve groundwater and improve livelihoods.

The total net irrigation requirements (i.e., groundwater withdrawals) for the optimal cropping pattern in wet, normal and dry scenarios are 61.40 × 10^5 m^3, 65.78 × 10^5 m^3, and 66.30 × 10^5 m^3, respectively (Table 1). The net incomes from the optimal cropping patterns for the wet, normal and dry scenarios are estimated at Rs. 81.83 million, Rs. 76.36 million and Rs. 71.55 million, respectively. It is apparent that from the wet scenario to dry scenario, there is a gradual increase in the net annual irrigation water use and a decrease in the net annual income from the crops. The net irrigation requirements for the government targeted cropping patterns were estimated at 85.06 × 10^5 m^3, 101.00 × 10^5 m^3 and 111.01 × 10^5 m^3 for the wet, normal and dry scenarios, respectively. Similarly, the net annual income from the government targeted cropping patterns were estimated at Rs. 63.81 million, Rs. 62.21 million and Rs. 61.21 million for the wet, normal and dry scenarios, respectively. Thus, if the optimal cropping patterns are adopted by the farmers in the study area, there will be saving in the irrigation water requirement by 23.66 × 10^5 m^3 (27.82%) in the wet scenario, 35.22 × 10^5 m^3 (34.87%) in the normal scenario, and 44.71 × 10^5 (40.28%) in the dry scenario. Additionally, there will be an increase in total net income by Rs. 18.02 million (28.24%), Rs. 14.15 million (22.75%) and Rs. 10.34 million (16.89%) in the wet, normal and dry scenarios, respectively.

5. CONCLUSIONS

The maximum allowable pumpage of the 69 tubewells obtained by the simulation-optimization model were found to be highest in the month of November and it gradually reduces to a minimum in the months of April and May. The total monthly maximum allowable groundwater withdrawals from the river basin were estimated at 1.63, 1.68, 1.60, 1.45, 1.60, 1.47 and 1.52 million m^3 in the months of November, December, January, February, March, April and May, respectively. The optimization model suggested a decrease in the area under post-monsoon paddy by 75% and an increase in the areas under crops like sugarcane, potato, onion, winter vegetables, summer vegetables and greengram by 50% over the existing areas. The net annual income from the optimal cropping patterns for the wet, normal and dry scenarios were estimated at Rs. 81.83 million, Rs. 76.36 million and Rs. 71.55 million, respectively. By adopting the optimal cropping patterns obtained from the optimization model, the net annual irrigation water requirement can be reduced by 23.66 ×10^5 m^3 and the net annual income can be enhanced by Rs. 18.02 million for the wet scenario. Similarly, there is a potential to decrease the net annual irrigation requirements by 35.22 ×10^5 m^3 and 44.71 ×10^5 m^3 and increase the net annual income by Rs. 14.15 million and Rs. 10.34 million for the normal and dry scenarios, respectively.

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