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OPTIMAL DEVELOPMENT OF GROUNDWATER IN A WELL COMMAND OF EASTERN INDIA USING INTEGRATED SIMULATION AND OPTIMIZATION MODELLING†

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ABSTRACT

Quantitative techniques such as simulation modelling and optimization play a vital role in the management of complex groundwater systems. This study demonstrates the combined use of groundwater-flow and resource optimization models to scientifically address the water scarcity problem in well-based command areas through a case study in eastern India. A transient simulation-optimization model was developed for the study area using Visual MODFLOW (groundwater-flow simulation tool) and the response-matrix technique to maximize pumping from the existing tubewells. The optimized maximum pumping rates obtained from the integrated simulation-optimization model were further used in linear programming-based optimization models to determine optimal cropping patterns for the 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. 81.8 million, Rs. 76.4 million and Rs. 71.6 million, respectively. The results of simulation-optimization modelling indicated that if the suggested optimal cropping patterns are adopted in the study area, the net annual irrigation water requirements will be reduced by 28, 35 and 40%, and net annual income will be increased by 28, 23 and 17% during wet, normal and dry scenarios, respectively. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: simulation-cum-optimization modelling; response matrix; optimal cropping pattern; groundwater management; well command area

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RÉSUMÉ

Les techniques quantitatives telles que la modélisation de simulation et d'optimisation jouent un rôle vital dans la gestion des systèmes complexes d'eaux souterraines. Cette étude de cas en Inde orientale démontre que l'utilisation combinée de modèles de prélèvement et de gestion de l'eau souterraine permet de s'attaquer au problème scientifiquement posé de la rareté de l'eau dans l'aire contributive d'un puits. Un modèle transitoire de simulation-optimisation a été développé pour la zone d'étude en utilisant, d'une part, Visual MODFLOW (outil de simulation de flux des eaux souterraines), et, d'autre part la technique de la réponse à matrice pour maximiser le pompage dans les forages existants. Les taux de pompage maximisés fournis par les modèles de gestion intégrée ont ensuite été utilisés dans les modèles de programmation linéaire afin de déterminer les assolements optimaux pour les scénarios humides, normaux et secs. Le revenu annuel optimal pour ces scénarios humides, normaux et secs a été estimé à 81.8 millions, 76.4 millions et 71.6 millions de roupies, respectivement. Les résultats de la modélisation indiquent que si les caractéristiques optimales de récolte proposées sont adoptées dans la zone d'étude, les besoins annuels nets en eau d'irrigation seront réduits de 28, 35 et 40 %, alors que le résultat net annuel sera augmenté de 28, 23 et 17 % au cours des scénarios humides, normaux et secs, respectivement. Copyright © 2013 John Wiley & Sons, Ltd.

MOTS CLÉS: simulation/optimisation de la modélisation; matrice de réponse; assolement optimal; gestion des eaux souterraines; aire contributive d'un puits

INTRODUCTION

Groundwater is a very important and invaluable natural resource on the earth. Its unique qualities of being easily accessible, generally free from pathogens and suspended

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† Le développement optimal des eaux souterraines dans l'aire contributive d'un puits de l'Inde orientale, en utilisant la simulation intégrée et des modèles d'optimisation.

particles, and requires no or little treatment, have made it the most important and preferred source of water for domestic, agricultural and industrial uses. It also serves as the only reliable source of water supply during emergency periods. However, aquifer depletion worldwide due to over-exploitation and the growing pollution of groundwater are threatening the sustainability of water supply and ecosystems on the earth (Shah *et al*., 2000; Zektser, 2000; Sophocleous, 2005; Biswas *et al*., 2009). Hence, a serious concern is how to maintain a long-term sustainable yield from aquifers (e.g. Hiscock *et al*., 2002; Alley and Leake, 2004) in the face of looming climate change and socio-economic changes.

In India, the demand for water has already increased manifold over the years due to growing urbanization, increasing population, agriculture expansion, rapid industrialization and economic development, and it has an increasing trend in all 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 (Central Ground Water Board (CGWB), 2006) and mismanagement. Excessive groundwater exploitation has led to an 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, analysis of GRACE satellite data has revealed that the groundwater reserves in the states of Rajasthan, Punjab and Haryana are being depleted at a rate of $17.7 \pm 4.5\,km^3\,yr^{-1}$ (Rodell *et al*., 2009). It was also found that between August 2002 and December 2008, the above-mentioned north-western states of India lost $109\,km^3$ of groundwater, which is double the capacity of India's largest reservoir Wainganga and almost triple the capacity of 'Lake Mead', the largest man-made reservoir in the United States (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. Therefore, efficient and judicious utilization of surface and groundwater resources is essential to protect vital groundwater resources as part of sustainable land and water management strategies.

The state of Odisha in eastern India is no exception and has its own share of water problems with diverse situations in different parts, such as 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 the uneven nature of rainfall and its capricious distribution, there is an increasing dependence on groundwater resources to meet the growing water demand from the agriculture, industrial and domestic sectors. The overexploitation of groundwater has resulted in declining groundwater levels in several areas and seawater intrusion in coastal areas (CGWB, 2006). Even though sufficient water is available in coastal areas in the monsoon (wet) season, there is a water shortage for irrigation in the post-monsoon (dry) season. Therefore, there is a need to develop optimal groundwater management strategies to increase the area under post-monsoon season crops and thereby sustain agricultural productivity and livelihoods.

Quantitative 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, minimizing adverse impacts on the environment, and for providing cost-effective management goals. In the last four decades, groundwater simulation models (Ting *et al*., 1998; Asghar *et al*., 2002; Lin and Medina, 2003; Sarwar and Eggers, 2006; Zume and Tarhule, 2008; Al-Salamah *et al*., 2011) and groundwater simulation-optimization models (Peralta and Datta, 1990; Hallaji and Yazicigil, 1996; Jonoski *et al*., 1997; Belaineh *et al*., 1999; Barlow *et al*., 2003; Uddameri and Kuchanur, 2007; Ahlfeld and Gemma, 2008; Safavi *et al*., 2010) 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 modelling studies are still in the 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, as yet very few studies on basin-wide groundwater-flow modelling (Ahmed and Umar, 2009; Raul *et al*., 2011) and groundwater simulation-cum-optimization modelling (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 in order to demonstrate the efficacy of combined groundwater-flow simulation and resource optimization models in developing efficient strategies for the sustainable management of groundwater in command areas dominated by well irrigation. To achieve this objective, a study area, the Kathajodi–Surua inter-basin, located in Orissa state in eastern India, was selected. The present study is first of its kind in the study area.

STUDY AREA

Location and climate

The study area, the Kathajodi–Surua inter-basin, is surrounded on both sides by the Kathajodi River and its branch the Surua. The study area is located around the confluence of the Mahanadi River with the Bay of Bengal along the eastern coast of India (Figures 1 and 2). It is located

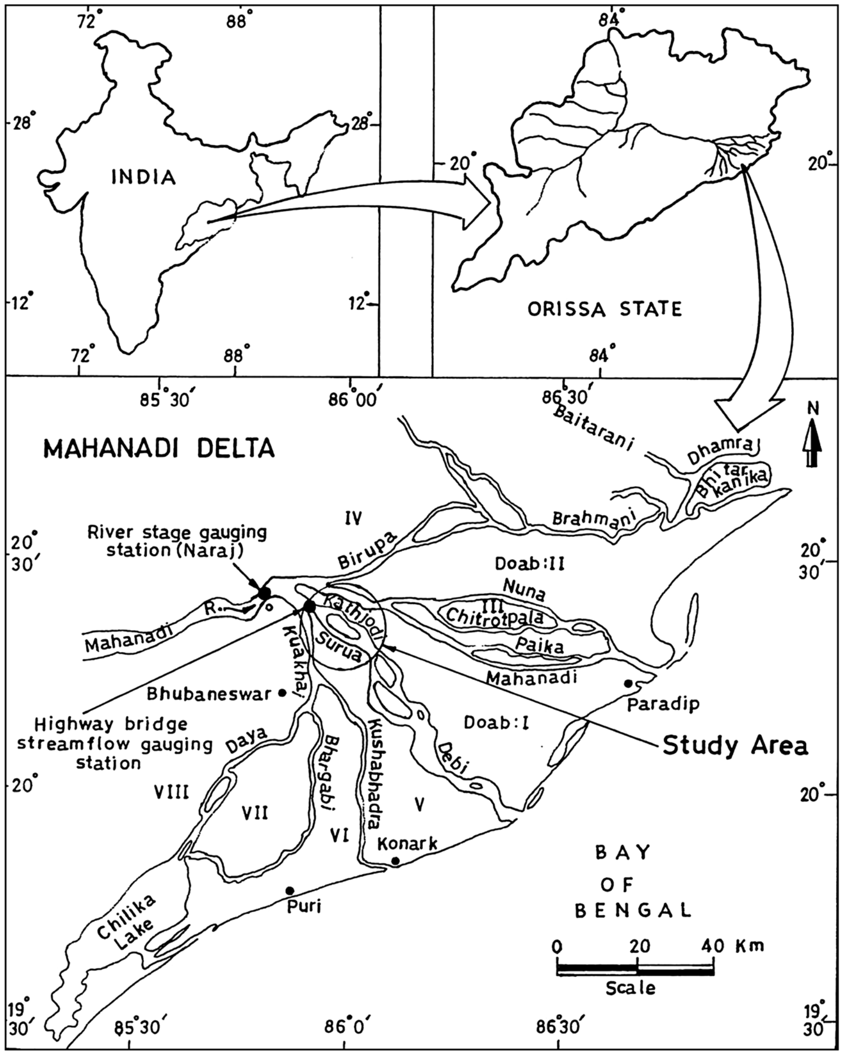

Figure 1. Map of the study area showing geographical location and other details

between 85°54'21" to 86°00'41" E and 20°21'48" to 20° 26'00" N. The total geographical area of the study area is 35 km^2. The area is characterized as a tropical humid climate with an average annual rainfall of 1650 mm, of which approximately 80% occurs during June to October.

Cropping pattern and irrigation scenario

Agriculture is the major occupation of the inhabitants. The total cultivated area in the study area is 2445 ha, of which 1365 ha (55.8%) is irrigated land. The area of low land is 408 ha (16.7%), medium land 1081 ha (44.2%) and high land 956 ha (39.1%). Paddy is the major crop in the monsoon season, whereas vegetables, potato, groundnut, greengram, blackgram and horsegram are grown in the post-monsoon season. Groundwater is the only source of irrigation in the study area. There are 69 functioning government tubewells in the area (Figure 2), which constitute major sources of groundwater withdrawal 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. Thus, the command area of this study area can be called a 'well command area', as opposed to the widely used term 'canal command area'.

As such, there is no water shortage during the monsoon (wet) season in the study area, but in the latter part of post-monsoon (dry) season, farm ponds and dug wells dry up and groundwater levels start to go down. As a result, water scarcity occurs 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 the sustainable management of water resources, particularly groundwater, in the study area.

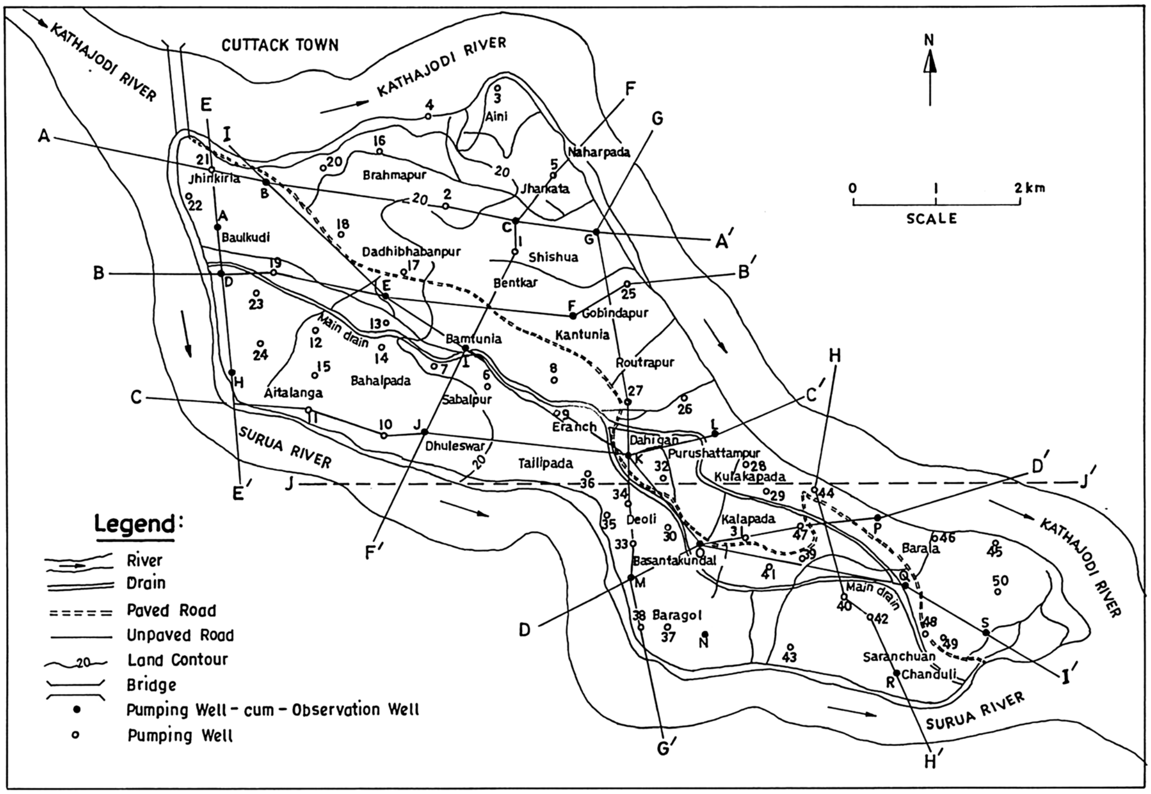

Figure 2. Location of observation and pumping wells and geological cross-sections in the study area

Hydrogeology and groundwater scenario

The detailed hydrological and hydrogeological investigations in the study area are presented in Mohanty *et al.* (2012). The river basin is underlain by a semi-confined aquifer which mostly comprises coarse sand. The thickness of the aquifer varies from 20 to 55 m and the depth from 15 to 50 m over the basin. The aquifer's hydraulic conductivity determined by pumping tests varies from 11.3 to 96.8 m day^{-1}, whereas the storage coefficient ranges between 1.43×10^{-4} and 9.9×10^{-4}. The annual recharge in the study area is estimated to vary from 288 to 385 mm (Mohanty, 2012). Analysis of river stage and groundwater level data indicated the existence of stream–aquifer interaction in the basin. Comparison of groundwater contour maps of dry and wet seasons indicated that there is about 3–4 m spatial variation and about 5–6 m seasonal variation of groundwater levels over the river basin.

MATERIALS AND METHODS

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 the Central Rice Research Institute (CRRI), Cuttack, Odisha, located about 2 km from the study area. The 20 years of rainfall data were analysed for investigation of annual and monthly variations of rainfall in the study area. Frequency analysis of the monthly rainfall data was also performed considering probability distribution functions of normal, 2-parameter log-normal, 3-parameter log-normal, Pearson type III, log Pearson type III, Gumbel type 1 extremal and generalized extreme value, 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 rainfall at 20, 50 and 80% exceedance of rainfall were found. Based on 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 the Odisha Lift Irrigation Corporation (OLIC) Office, Cuttack, Odisha. The lithologic data were analysed in detail, which along with other field data were used to develop a numerical groundwater-flow model of the study area. Since no groundwater data were available in the study area, a groundwater monitoring programme was initiated by the authors. Monitoring of groundwater levels in the study area was carried out by selecting 19 tubewells in such a way that they represent approximately four west-east and four north–south cross-sections of the study area. The locations of the 19 monitoring-cum-pumping wells are shown as filled circles (A to S) and the locations of other 50 pumping wells are shown as open circles (1 to 50) in Figure 2. Weekly groundwater-level data at the 19 sites were monitored from February 2004 to October 2007, and were used for studying the groundwater characteristics in the study area and calibration of the groundwater-flow simulation model. The river stage data at 10 sections were monitored on a monthly basis and were used for assigning boundary conditions to the groundwater-flow simulation model.

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 the 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, which are given in Table I. The water requirements of these crops (i.e. ET_c) were determined by the pan evaporation method (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998) as follows:

$$ET_o = K_p \times E_{pan} \tag{1}$$

$$ET_{crop} = k_c \times ET_o \tag{2}$$

where ET_o = reference evapotranspiration (mm day^{-1}), K_p = pan coefficient, E_{pan} = pan evaporation (mm day^{-1}), ET_{crop} = crop evapotranspiration (mm day^{-1}), and k_c = crop coefficient.

Given the water requirements of the crops, the net irrigation requirements of the crops were calculated by deducting the effective rainfall from the water requirements of the crops. The effective rainfall was estimated by the USDA-SCS method (Doorenbos and Pruitt, 1977).

Table I. Targeted area of coverage under different post-monsoon crops

Sl. No.	Crop	Area (ha)
1	Paddy	710
2	Sugarcane	130
3	Potato	200
4	Onion	20
5	Groundnut	82
6	Winter vegetables	400
7	Summer vegetables	165
8	Greengram	210
9	Blackgram	320
10	Horsegram	150
11	Mustard	36

Development of groundwater-flow simulation model

A groundwater-flow simulation model of the study area was developed using Visual MODFLOW software to analyse groundwater conditions in the study area. The model was developed following the groundwater modelling protocol (Anderson and Woessner, 1992), which consisted of three main phases: conceptual model development, model design, and model calibration and validation.

Conceptual model. The conceptual model of the aquifer system prevalent in the study area was developed based on hydrogeological investigations. The thickness of the aquifer varies from 20 to 55 m and its depth from the ground surface varies from 15 to 50 m over the basin. The aquifer material comprises medium sand to coarse sand, whereas the upper confining layer mostly consists of clay. There are patches of medium and coarse sand within the clay bed which are most likely to be leaky in nature. Also, there are some clay lenses present in the study area. To simplify the actual field situation for groundwater-flow modelling, these clay lenses were ignored when developing the conceptual model of the study area. The eastern boundary of the study area is the Kathajodi River and the western boundary the Surua River (Figure 2). Therefore, these boundaries were simulated as Cauchy boundary conditions. The conceptual model of the study area along Section J–J' (Figure 2) is illustrated in Figure 3, which provided a basis for the design and development of a numerical groundwater-flow model of the study area.

Numerical model design. The study area was discretized into 40 rows and 60 columns using the Grid module of the Visual MODFLOW software. This resulted in 2400 rectangular cells, with a dimension of approximately 222 × 215 m. The river boundaries were simulated as Cauchy boundary conditions and the base of the aquifer modelled as a no-flow boundary. The location of pumping wells, observation wells, and extent of the well screens of respective pumping wells were assigned to the model. The model parameters such as hydraulic conductivity, specific storage, groundwater abstraction in all the pumping wells and groundwater recharge were provided as inputs to the model.

Model calibration and validation. The developed numerical groundwater-flow model was calibrated using weekly groundwater-level data of 19 sites from February 2004 to May 2006. Hydraulic conductivity, specific storage and recharge were used as calibration parameters. Thereafter, the calibrated model was validated using weekly groundwater-level data from June 2006 to May 2007. The results of model calibration and validation were evaluated

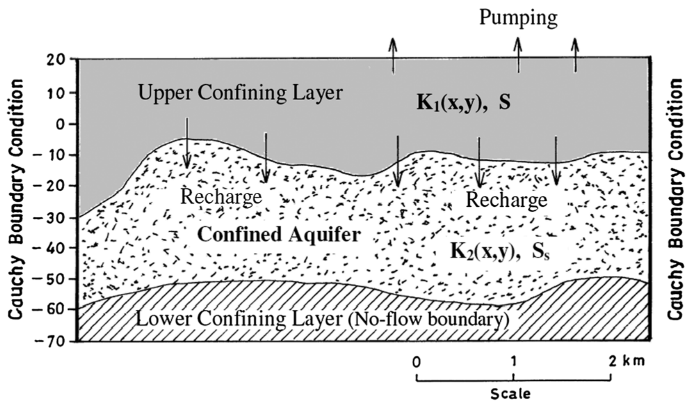

Figure 3. Conceptual model of the study area

using goodness-of-fit criteria such as residual mean, absolute residual mean, standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE and correlation coefficient (*r*). Also, scatter plots of observed and simulated groundwater levels, together with 1 : 1 line, 95% interval lines and 95% confidence interval lines were prepared in order to examine the efficacy of the flow models in simulating groundwater levels.

Development of simulation-optimization model

Generation of response matrices. The calibrated and validated 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 (Hallaji and Yazicigil, 1996; Theodossiou, 2004). A transient response function in the discrete form is given as (Maddock, 1972)

$$s_{kn} = \sum_{i=1}^{\mathrm{NPW}} \sum_{j=1}^{n} \beta_{ki(n-j+1)} q_{ij} \tag{3}$$

where S_{kn} = drawdown at site k at the end of total pumping period n (m), $\beta_{ki(n\text{-}j+1)}$ = average drawdown at site k at the end of pumping period n due to a unit pulse of pumpage at the ith well during the jth pumping period (s m^{-2}), q_{ij} = average discharge at the ith well during the jth pumping period (m^3 s^{-1}), 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 the simulation-optimization model. Consequently, transient response functions $\beta_{ki(n\text{-}j+1)}$ 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 discharge of 1 l s^{-1} for the first 1 month period and zero discharge for the rest of the 6 months. Drawdowns at 69 pumping wells were simulated by pumping of the wells over the 7-month pumping period. The response functions thus obtained (a total of 33 327) were then assembled to form a transient response matrix. The response-function approach is usually applicable to a linear system, i.e. a confined aquifer system (Hallaji and Yazicigil, 1996). Since the Kathajodi–Surua inter-basin comprises a confined aquifer, use of this approach in this study is justified.

Formulation of the 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 maximum drawdowns in the aquifer usually occur at pumping well sites. The prediction of hydraulic head or drawdown at each well location as a response to the pumping is of great interest for proper groundwater planning and management. This response was represented in terms of a response matrix as described in the previous section. In the hydraulic management model, drawdowns at all the 69 wells were constrained so that the cumulative effect of pumping from all the wells does not exceed the maximum allowable drawdown at individual wells. Constraints were also introduced to ensure that the annual water demand of the study area is met to the maximum extent possible. A final consideration was the physical capability of the system imposed by well capacity limitations. The objective function of the model was to maximize the total pumpage from the basin. That is,

$$\text{Max}Q = \sum_{i=1}^{69}\sum_{j=1}^{7} q_{ij}d_j \tag{4}$$

where Q = total pumpage from the existing wells (m^3); q_{ij} = pumpage of the ith well in the jth month (m^3 s^{-1}); d_j = number of days of pumping in the jth 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). When applying Equation (4), it was assumed that the pumps are operated for maximum 12 h a day.

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

- *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):

$$\sum_{i=1}^{69}\sum_{j=1}^{7} \beta_{ki(n-j+1)} q_{ij} \le S_k^{\max}, k = 1, 2, 3 \ldots 69 \tag{5}$$

where $\beta_{ki(n\text{-}j+1)}$ = average drawdown at the kth site due to a unit pulse of pumpage at the ith well during the jth month; n = total number of time periods; k = index for site number; $S_k^{\max}$ = maximum allowable drawdown at the kth site (m);

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

$$\sum_{i=1}^{69} q_{ij}d_j \ge D_j, \quad j = 1, 2 \ldots 7 \tag{6}$$

where D_j = water demand of the crops in the jth month (m^3); d_j = number of days of pumping in the jth month;

- *pumping capacity constraints*. The pumping in individual wells cannot exceed the pumping capacity of the wells and it has to be a positive value. That is,

$$0 \le q_{ij} \le q_{ij}^{\max}, i = 1, 2, 3 \ldots 69; j = 1, 2 \ldots 7 \tag{7}$$

where $q_{ij}^{\max}$ = maximum pumping capacity of the ith well in the jth month.

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

Inputs of the hydraulic management model. The inputs of the hydraulic management model are the monthly water demands of the crops, drawdown coefficients $\beta_{ki(n-j+1)}$, maximum permissible drawdowns $S_k^{\max}$ at 69 well sites, and maximum rates of pumping of the wells. At present, the farmers in the study area operate their pumps without any restrictions. As a result, the pumping from each well is at its maximum capacity during the dry non-monsoon period. Therefore, the upper limits of pumpage from individual wells in the months of November to May were considered to be the current rates of pumping during these months. The maximum possible drawdown at a site could be determined considering the pumping cost, land subsidence and other socio-scientific factors. In this study, the drawdown in individual wells during the dry period was considered as the maximum permissible drawdown which is summarized in Table II.

Optimization model for land and water resources management

The transient hydraulic management model estimates the maximum permissible pumpage from the groundwater reservoir by the existing pumping wells. With the available land and water resources, a linear programming optimization model was formulated to determine the 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

Table II. Maximum permissible drawdowns ($S_{\max}$) at 69 sites over the study area

Site	$S_{\max}$ (m)	Site	$S_{\max}$ (m)	Site	$S_{\max}$ (m)
A	6.78	5	5.72	28	4.08
B	7.40	6	6.80	29	4.08
C	7.67	7	5.80	30	4.74
D	6.80	8	6.76	31	4.74
E	7.03	9	6.80	32	4.63
F	6.76	10	5.82	33	4.57
G	5.72	11	6.82	34	4.63
H	7.03	12	7.03	35	4.57
I	6.80	13	7.03	36	4.63
J	5.82	14	7.03	37	3.92
K	4.63	15	7.03	38	3.92
L	4.08	16	7.40	39	4.16
M	4.57	17	7.03	40	4.64
N	3.92	18	7.40	41	4.74
O	4.74	19	6.80	42	4.64
P	4.16	20	7.40	43	4.23
Q	4.64	21	6.78	44	4.16
R	4.23	22	6.78	45	4.64
S	4.64	23	6.80	46	4.16
1	7.67	24	7.03	47	4.16
2	7.67	25	5.76	48	4.64
3	7.67	26	4.08	49	4.64
4	7.67	27	4.63	50	4.64

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.

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:

$$MaxZ = \sum_{i=1}^{3}\sum_{j=1}^{11}\left(P_jY_j - C_j - I_{ij}\right)a_{ij} \tag{8}$$

where Z = net total annual income corresponding to wet, normal and dry scenarios (Rs.); P_j = market price of the jth crop (Rs. kg^{-1}); Y_j = yield of the jth crop (kg ha^{-1}); C_j = cost of cultivation per unit area for the jth crop excluding the cost of irrigation water (Rs. ha^{-1}); I_{ij} = irrigation cost for the jth crop in the ith type of land (Rs. ha^{-1}); a_{ij} = area under the jth crop in the ith 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:

- *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,

$$\sum_{j=1}^{11} a_{ij} \leq A_i;\, i = 1, 2, 3 \tag{9}$$

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

- *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:

$$\sum_{i=1}^{3}\sum_{j=1}^{11} a_{ijk}.w_{ijk} \leq W_k;\, k = 1, 2, \ldots, 7 \tag{10}$$

where a_{ijk} = area under the jth crop in the ith type of land in the kth month, w_{ijk} = water requirement of the jth crop in the ith type of land in the kth month, W_k = available irrigation water (i.e. maximum groundwater withdrawals) in the kth 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:

$$W_k = \eta\sum_{i=1}^{69} q_{ik}d_k;\, k = 1, 2, \ldots, 7 \tag{11}$$

where η = irrigation efficiency, q_{ik} = maximum allowable pumpage of the ith well in the kth month (m^3 s^{-1}); d_k = number of days of pumping in the kth month (k = 1 for January, k = 2 for February, . . . , and k = 7 for May).

- *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

$$A_j^L \leq \sum_{i=1}^{3} a_{ij} \leq A_j^U;\, j = 1, 2, 3, \ldots 11 \tag{12}$$

where A_j^L = minimum area under the jth crop, and A_j^U = maximum area under the jth crop.

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

Inputs of the optimization model

Inputs to the management model include the total area under high, medium and low land, maximum and minimum areas under different crops, water requirement of crops in different months in different land types under different scenarios (i.e. wet, normal and dry), and net income from the crops in different land types in each scenario. 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, medium and low land are 956, 1081 and 408 ha, respectively. The maximum area of each crop was fixed as 50% more than the targeted area, considering the practical feasibility and farmers' interest. The minimum area under each crop was fixed as one quarter of the targeted area considering the preference of the local farmers. The cost of cultivation including cost of irrigation of the above-mentioned crops was computed by standard methodology followed by the Commission for Agricultural Costs and Prices (CACP), India. The mean yield of the crops and selling price of the crop produce in the market were obtained from agriculture statistics, Directorate of Economics and Statistics, Government of Odisha, India. The net irrigation requirement in different crops in different land types, i.e. low, medium and high land, were calculated based on the data obtained from the Department of Agriculture, Government of Odisha. Finally, the net incomes from the crops under different land types for the three scenarios were calculated. Further, an irrigation efficiency of 90% was considered in this study because only groundwater is used in the study area for irrigation.

RESULTS AND DISCUSSION

Rainfall characteristics

Analysis of 20 years (1990–2009) of rainfall data in the study area indicated an average annual rainfall of 1650 ± 376 mm. The highest mean monthly rainfall (403 mm) with a standard deviation of 194 mm was observed in the month of August. Though rainfall events are distributed throughout the year, the rainy season usually starts from mid-June and lasts up to mid-October. November to May is usually characterized as a dry period. The most reliable months for rainfall are July, August and September. The probability analysis of the monthly rainfall data indicated that two-parameter log normal distribution is the best fit to the rainfall data of January, February, March and December; Pearson type III distribution for April and November; log Pearson type III distribution for May, June, August and October; Gumbel type 1 extremal distribution for the month of July and normal distribution for the month of September. Figure 4 shows the temporal variation of monthly rainfall during wet, normal and dry scenarios. Clearly, there is a considerable variation in the amount of monthly rainfall during wet and dry scenarios.

Crop water requirement

The net depth of irrigation requirements of different crops for the wet, normal and dry scenarios are shown in Table III. The net irrigation requirements of paddy in the wet, normal and dry scenarios are 875, 938 and 999 mm, respectively. The increase in net irrigation requirement of crops from the dry to normal scenario varied from a minimum 7.2% in the case of paddy to a maximum of 84.8% in the case of summer vegetables. However, the increase in net irrigation requirement of crops from the normal to wet scenario varied from a minimum of 6% in the case of onion to a maximum of 24.3% in the case of summer vegetables.

Table III. Net irrigation requirements of the *rabi* crops under different scenarios

Crop	Net irrigation requirement (mm)		
	Wet scenario	Normal scenario	Dry scenario
Paddy	875	938	999
Sugarcane	308	458	529
Potato	219	261	277
Onion	224	266	282
Groundnut	199	241	257
Winter vegetables	184	237	255
Summer vegetables	118	218	271
Greengram	110	138	150
Blackgram	115	146	158
Horsegram	133	172	188
Mustard	154	192	210

The total crop water requirements in the months of November, December, January, February, March, April and May were estimated at 4.8×10^5, 9.0×10^5 , 26.5×10^5, 22.7×10^5, 24.7×10^5, 22.2×10^5 and 8.1×10^5 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 73.9×10^5, 7.5×10^5, 5.8×10^5, 0.6×10^5, 2.2×10^5, 10.7×10^5, 5.0×10^5, 3.3×10^5, 5.2×10^5, 3.0×10^5 and 0.8×10^5 m^3, respectively.

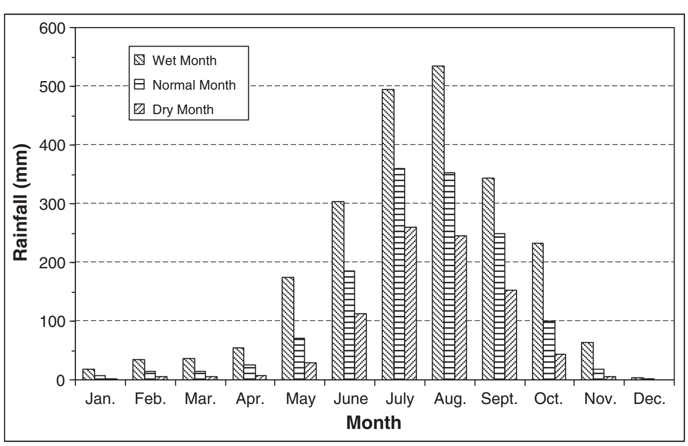

Figure 4. Monthly variation of rainfall during wet, normal and dry scenarios

Model validation results

The scatter diagram along with 1 : 1 line, 95% interval lines and 95% confidence interval lines for the validation is shown in Figure 5. It is obvious that the 1 : 1 line lies within the 95% confidence interval lines which indicates satisfactory validation of the developed groundwater-flow model. The residual mean, absolute residual mean, SEE, RMSE, normalized RMSE and correlation coefficient between observed and simulated groundwater levels were found to be 0.044 m, 0.489 m, 0.02 m, 0.632 m, 6.527% and 0.958, respectively (Figure 5). These goodness-of-fit criteria show that there is a reasonably good calibration and validation of the groundwater-flow simulation model.

Maximum permissible groundwater withdrawal

The value of maximum permissible pumpage was highest in the months of November and December, thereafter gradually reducing 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 was 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 the optimal cropping pattern and optimal pumping schedule for the study area.

Furthermore, it was found that the optimized maximum permissible pumping rates in different months are mostly determined as the maximum assigned discharge of the wells in a particular month. Thus, the optimum pumping rates of each well have been limited due to the capacity of the pumps installed, which is lower than the actual well yield. Using the optimized pumping rates as inputs, the model was run to simulate groundwater levels. The difference between simulated drawdowns and specified drawdown constraints (i.e. maximum allowable drawdown) varied from 1.4 to 2.6 m.

Optimal cropping pattern and groundwater allocation

The optimal allocation of different crops to different land types, the optimal allocation of groundwater (i.e. net irrigation requirement) to different crops and the net annual income from the optimal cropping patterns in the wet, normal and dry scenarios are presented in Tables IV (a–c), respectively. The crops such as sugarcane, potato, onion, winter and summer vegetables have been allotted the maximum area possible in all three scenarios, because their net incomes are higher. The greengram crop has also been allotted the maximum area possible in all three scenarios,

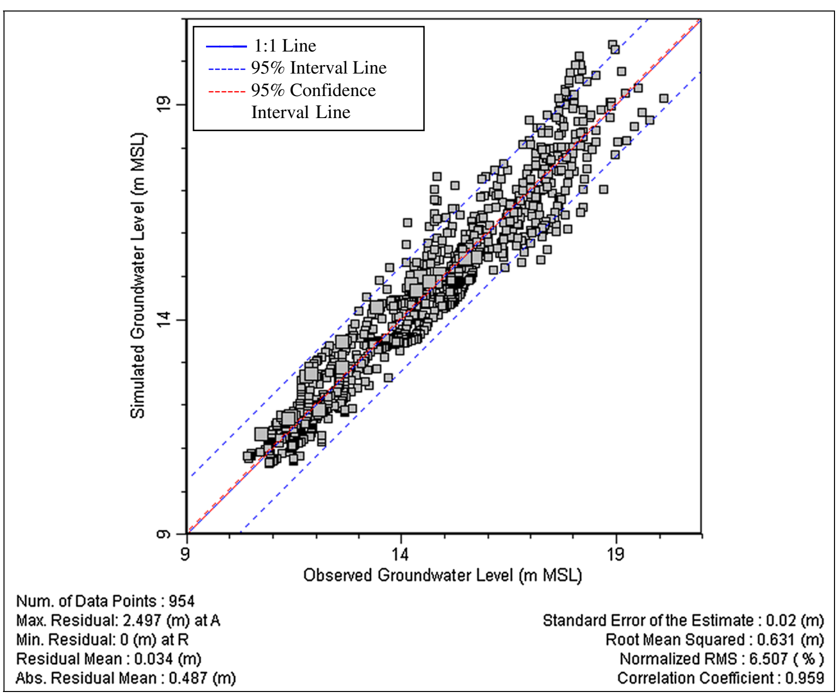

Figure 5. Scatter diagram of observed versus simulated groundwater levels for the validation period. This figure is available in colour online at wileyonlinelibrary.com/journal/ird.

Table IV. Optimal cropping pattern, net irrigation requirement and net annual income for the (a) *wet* scenario, (b) *normal scenario*, and (c) *dry* scenario

(a)	Allocated land (ha)				
Crop	Low land	Medium land	High land	Total	Net irrigation requirement (m^3)
Paddy	304	–	-	304	24.6×10^5
Sugarcane	-	195	-	195	5.7×10^5
Potato	-	-	300	300	6.4×10^5
Onion	-	-	30	30	0.7×10^5
Groundnut	-	-	123	123	2.4×10^5
Winter vegetables	104	496	-	600	9.4×10^5
Summer vegetables	-	-	248	248	2.9×10^5
Greengram	-	-	315	315	3.2×10^5
Blackgram	-	336	144	480	4.8×10^5
Horsegram	-	-	44	44	0.6×10^5
Mustard	-	54	-	54	0.74×10^5
Total	408	1081	1204	2693	61.4×10^5
Net annual income = Rs. 81.8×10^6					

Note: 1 US$ = Rs. 55 (approximately).

(b)	Allocated land (ha)				
Crop	Low land	Medium land	High land	Total	Net irrigation requirement (m^3)
Paddy	177	-	-	177	16.0×10^5
Sugarcane	-	195	-	195	8.7×10^5
Potato	-	-	300	300	7.8×10^5
Onion	-	-	30	30	0.8×10^5
Groundnut	-	-	123	123	3.0×10^5
Winter vegetables	231	369	-	600	12.7×10^5
Summer vegetables	-	-	248	248	5.4×10^5
Greengram	-	315	-	315	4.0×10^5
Blackgram	-	193	92	285	3.9×10^5
Horsegram	-	-	202	202	3.5×10^5
Mustard	-	9	-	9	0.2×10^5
Total	408	1081	995	2484	65.8×10^5
Net annual income = Rs. 76.4×10^6					

(c)	Allocated land (ha)				
Crop	Low land	Medium land	High land	Total	Net irrigation requirement (m^3)
Paddy	177	-	-	177	17.4×10^5
Sugarcane	-	195	-	195	10.2×10^5
Potato	-	62	238	300	8.3×10^5
Onion	-	30	-	30	0.8×10^5
Groundnut	-	-	52	52	1.3×10^5
Winter vegetables	222	378	-	600	14.6×10^5
Summer vegetables	-	-	248	248	6.7×10^5
Greengram	-	315	-	315	4.5×10^5
Blackgram	-	101	-	101	1.5×10^5
Horsegram	-	-	37	37	0.7×10^5
Mustard	9	-	-	9	0.2×10^5
Total	408	1081	575	2064	66.3×10^5
Net annual income = Rs. 71.6×10^6					

whereas the groundnut crop is allotted the maximum area possible only in the 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 crops like groundnut and greengram, its area has been limited due to higher water requirement. This finding suggests that paddy cultivation by groundwater should be minimized by adopting crop diversification. Such a strategy is necessary to conserve groundwater resources and protect them from depletion while ensuring enhanced income to the farmers.

Tables IV (a–c) show that total cropped area under high lands in the wet, normal and dry scenarios are 1204, 995 and 575 ha, respectively. However, as the cropping periods of potato, onion, groundnut, greengram, blackgram and horsegram under high lands are exclusive of the cropping period of summer vegetables, the total maximum area under high lands at a particular time in the wet, normal and dry scenarios are 956, 747 and 327 ha respectively. These figures are obtained by deducting the area under summer vegetables (i.e. 248 ha) from the total area under high land in the respective scenarios [Tables IV (a–c)]. Therefore, all the areas under low land (408 ha), medium land (1081 ha) and high land (956 ha) have been covered under crops in the wet scenario, whereas in the normal and dry scenarios, only the entire low and medium land have been covered under crops. The decrease in total cropped area under high land in the normal scenario (747 ha) and dry scenario (327 ha) is due to the relative shortage of irrigation water during these two scenarios.

It is worth mentioning that the optimization model suggests total cropped areas of 2693, 2484 and 2064 ha in the 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 the wet, normal and dry scenarios are 61.4×10^5, 65.8×10^5 and 66.3×10^5 m^3, respectively [Tables IV (a–c)]. The net incomes from the optimal cropping patterns for the wet, normal and dry scenarios are estimated at Rs. 81.8 million, Rs. 76.4 million and Rs. 71.6 million, respectively. It is apparent that from the wet to the dry scenario, there is a gradual increase in net annual irrigation water use and a decrease in net annual income from the crops. Figure 6 shows the comparison of net irrigation requirement between the government-targeted cropping pattern and the optimal cropping pattern in different scenarios. The net irrigation requirements for the government-targeted cropping patterns are 85.1×10^5, 101×10^5 and 111×10^5 m^3 for the wet, normal and dry scenarios, respectively. Similarly, Figure 7 shows the comparison of net annual income between the government-targeted cropping pattern and the optimal cropping pattern in different scenarios. The net annual income from the government- targeted cropping patterns are Rs. 63.8 million, Rs. 62.2 million and Rs. 61.2 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 irrigation water requirement of 23.7×10^5 m^3 (27.8%) in the wet scenario, 35.2×10^5 m^3 (34.9%) in the normal scenario, and 44.7×10^5 m^3 (40.3%) in the dry scenario. Additionally, there will be an increase in total net income of Rs. 18.0 million (28.2%), Rs. 14.2 million (22.8%) and Rs. 10.3 million (16.9%) in the wet, normal and dry scenarios, respectively.

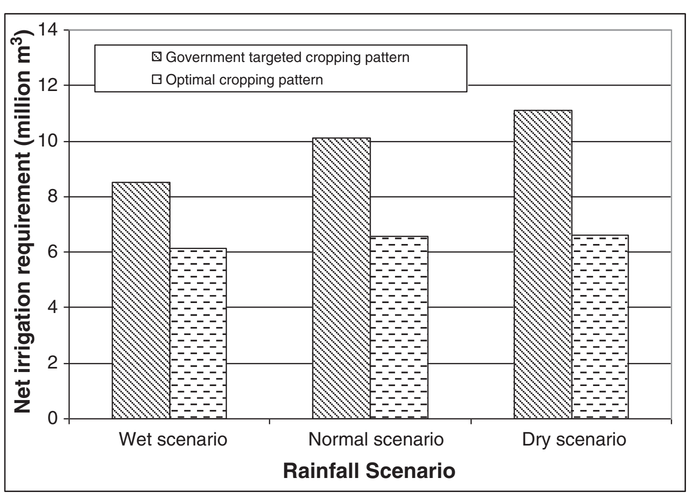

Figure 6. Comparison of net irrigation requirements between government-targeted cropping pattern and optimal cropping pattern under different scenarios

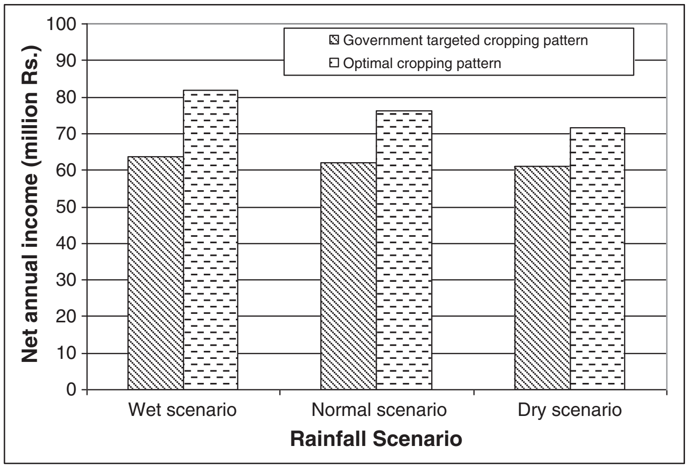

Figure 7. Comparison of net annual income between government-targeted cropping pattern and optimal cropping pattern under different scenarios

CONCLUSIONS

The present study was undertaken to demonstrate the efficacy of combined groundwater-flow simulation and resource optimization models in the sustainable management of groundwater in well-based command areas. The desired goal was achieved through a case study area located in Odisha, eastern India. A transient groundwater-flow simulation-cum-optimization model was developed for the study area using Visual MODFLOW (groundwater-flow simulation tool based on finite difference method) and the response-matrix technique to maximize pumping from existing tubewells. Finally, optimization models using the linear programming method were developed to determine optimal cropping patterns for the wet, normal and dry scenarios.

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. 81.8 million, Rs. 76.4 million and Rs. 71.6 million, respectively. By adopting the optimal cropping patterns obtained from the optimization model, the net annual irrigation water requirement can be reduced by $23.7 \times 10^5\, m^3$, and the net annual income can be enhanced by Rs. 18.0 million for the wet scenario. Similarly, there is a potential to decrease the net annual irrigation requirements by $35.2 \times 10^5\, m^3$ and $44.7 \times 10^5\, m^3$ and increase the net annual income by Rs. 14.2 million and Rs. 10.3 million for the normal and dry scenarios, respectively.

Overall, the findings of this study are very useful to the planners and decision makers concerned, and based on the results of this study, management strategies could be formulated for the efficient utilization of water and land resources in the study area. The methodology demonstrated in this study being generic, it is also useful for other river basins.

NOTE

[1](Rs. = Indian rupee, 1 rupee = 0.0182 US$, price level 2012).

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