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Simulation Modeling for Efficient Groundwater Management in Balasore Coastal Basin, India

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Abstract The Balasore coastal groundwater basin in Orissa, India is under a serious threat of overdraft and seawater intrusion. The overexploitation resulted in abandoning many shallow tubewells in the basin. The main intent of this study is the development of a 2-D groundwater flow and transport model of the basin using the Visual MODFLOW package for analyzing the aquifer response to various pumping strategies. The simulation model was calibrated and validated satisfactorily. Using the validated model, the groundwater response to five pumping scenarios under existing cropping conditions was simulated. The results of the sensitivity analysis indicated that the Balasore aquifer system is more susceptible to the river seepage, recharge from rainfall and interflow than the horizontal and vertical hydraulic conductivities and specific storage. Finally, based on the modeling results, salient management strategies are suggested for the long-term sustainability of vital groundwater resources of the Balasore groundwater basin. The most promising management strategy for the Balasore basin could be: a reduction in the pumpage from the second aquifer by 50% in the downstream region and an increase in the pumpage to 150% from the first and second aquifer at potential locations.

Key words simulation · hydrogeology · coastal basin

1 Introduction

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Most of the water of our planet (97.5%)

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occurs as saltwater in the oceans. Of the remaining 2.5%, two-thirds occur as snow and ice in polar and mountainous regions, which leave only about 1% of the global water as liquid freshwater (Gupta 1992). It has been estimated that about 98.7% of all liquid freshwater is available as groundwater, while only 0.98% is available in rivers and lakes (Ayibotele 1992). Out of the total groundwater, 50% is available within the top 800 m of the earth's crust, which is accessible to human use. During the last few decades, groundwater has become an important source of freshwater throughout the world. It provides about one-third of the world's freshwater consumption (Moreaux and Reynaud 2005). However, overdraft is distorting the natural recharge-discharge equilibrium and thereby resulting in declining groundwater levels, which lead to freshwater scarcity, saltwater intrusion and land subsidence worldwide (Dooge 1993). It is estimated that if the current trend continues, about two-thirds of global population will face moderate to severe water stress by 2025 (Kuylenstierna et al. 1997a, b). Therefore, in order to avoid such consequences of overdraft, it is important to understand the behaviour of an aquifer system subjected to artificial stresses. Simulation modeling is an excellent tool to achieve this goal. Although several software packages are available for groundwater flow and transport simulation, in this study Visual MODFLOW has been used. Visual MODFLOW model has been used worldwide because of its easy accessibility, user-friendliness and versatility (Kashaigili et al. 2003). Rao et al. (2004) developed a density-dependent groundwater flow and transport model using SEAWAT model for simulating the dynamics of seawater intrusion and the simulated annealing algorithm for solving the optimization problem. Rao et al. (2005) also conducted studies for planning groundwater developments in coastal deltas with paleo channels using SEAWAT model and simulated annealing algorithm.

According to the Ministry of Water Resources, Government of India, the groundwater level in the 16 states of India has dropped to more than 4 m during the 1981–2000 period. Among the states, several pockets in 31 districts of Maharashtra, 30 in Madhya Pradesh, 23 in Andhra Pradesh, 21 in Karnataka, 20 in Uttar Pradesh (including Uttaranchal) and 19 districts in Orissa are reported to have depleting groundwater (Nigam and Subramaniam 2001). In Orissa, 15,000 villages in 28 out of 30 districts were affected by drought-like situation (Government of India 2001). About 119.50 lakh human populations, 65.54 lakh cattle population and 11.00 lakh ha crops were affected. Particularly, the western part of Orissa is facing acute drinking water crisis almost every year due to large-scale deforestation, unplanned use of irrigation water, unscientific/poor water management, and the lack of awareness for water conservation. About 3 million people are severely affected by this unfortunate situation. If the present trend continues, the water problem in Orissa will be much worse in the days to come.

Balasore groundwater basin of Orissa in Eastern India was selected as a study area. It is a coastal basin, which is plagued with declining groundwater levels and seawater intrusion (Rejani et al. 2003; Sethi et al. 2002). In the basin, agriculture is the main occupation of the people with 71% of the total workforce engaged in agriculture and the major source of irrigation is groundwater with a few river lift projects (CGWB 1999). Excessive pumping of groundwater for rice cultivation in the area, especially during non-monsoon seasons has resulted in declining groundwater levels and seawater intrusion into the basin (CGWB 1999; Annual Report 1992; OLIC 1999). With the onset of irrigation in the month of January–February, the water table falls abruptly by even more than 4 m in some places as a result of excessive pumping (CGWB 1999; Personal Communication 2000b). Long-term trend of groundwater level based on 12 years (1986–1997) data shows that there is a net decline of 0.35–2.5 m in the Balasore District (CGWB 1999). Many shallow tubewells and dugwells become inoperative as the groundwater level falls beyond the suction limit of conventional centrifugal pumps during the non-monsoon season. As a result, vast areas having shallow tubewells remain barren during non-monsoon season. Many of these shallow tubewells and dugwells happen to be the major sources of drinking water for a large community. Even during the normal hydrologic year, access to drinking water is assured only for 60% of the population. Much worse situation exists during drought years. The depleting groundwater resources in general and groundwater lowering after the month of February in particular is compelling the local people to depend on the water resources unfit for human consumption. Thus, the Balasore basin is under a serious threat of freshwater scarcity and poses questions about the sustainability of groundwater resources in the basin. Undoubtedly, proper planning and efficient management of groundwater resources is the need of the hour for ensuring their long-term sustainability.

For the past 20 years, various studies have been taken up for the simulation of flow and seawater intrusion using sharp interface approach or miscible approach. The simulation models were developed with finite element or finite difference techniques. For example, Huyakorn et al. (1987) developed a three-dimensional finite-element model for the simulation of seawater intrusion in single and multiple coastal aquifer systems with either a confined or phreatic top aquifer. They simulated the density-dependent seawater intrusion in coastal aquifers based on two governing equations, one for fluid flow and the other for salt transport. However, in many cases, a steady-state simulation in transient simulations was not obtained because of high computing costs. Nishikawa (1998) used MODFLOW for groundwater flow simulation and for saltwater, equivalent freshwater heads were considered. Ting et al. (1998) developed a preliminary groundwater-flow model using MODFLOW for water resources management in the Pingtung Plain, Taiwan. The transient calibration was done using trial and error adjustment of parameters and a sensitivity analysis of the model was also performed. Five major parameters used for the sensitivity analysis were phreatic storage factor, transmissivity, storage coefficient, vertical conductance and hydrogeological stresses like areal recharge and discharge. Asghar et al. (2002) used two groundwater models namely, MODFLOW and MT 3D to model the interface movement in an unconfined aquifer of Punjab, Pakistan. The results indicated that skimming wells of 10–18 l/s can be installed and operated successfully with 60–70% well penetration ratio for an operating time of 8–24 h/day from an unconfined aquifer having 15–18 m thick relatively fresh groundwater lens.

Gates and Grismer (1989) developed a finite difference model using Groundwater Modeling System (GMS) software package to analyze and predict water table elevations and salinity, flow of water and salts in and between the shallow aquifer, the river and the irrigation-drainage system. The model was applied in the salinity threatened lower Arkansas River Basin of Colorado. Lin and Medina (2003) incorporated the transient storage concept in modeling solute transport in the conjunctive stream-aquifer model. Three well-documented and widely-used USGS models were coupled to form the core of this conjunctive model: MODFLOW, DAFLOW MOC3D. Bauer et al. (2005) used SEAWAT software package for coupled flow/transport simulations for the Shashe River Valley in Botswana. They found that the salinity distribution in and around the Shashe River Valley as well as its temporal dynamics can be satisfactorily reproduced if the transpiration is modelled as a function of groundwater salinity. It is clear from the above reviews that the direction of groundwater modeling is towards the use of user-friendly and numerically robust software packages developed for flow and transport modeling.

Considering this fact, the present study was initiated to develop a two-dimensional groundwater flow and transport model for the coastal basin using Visual MODFLOW for the simulation of salient pumping strategies under existing agricultural practice so as to gain insights about the groundwater system as well as to minimize seawater intrusion and sustain groundwater utilization on a long-term basis. The present study is the first of its kind in the study area and a follow-up of the previous study (Rejani et al. 2003), which focused on the hydrogeologic analysis, estimation of crop evapotranspiration and gross irrigation requirement for the existing cropping pattern as well as the estimation of runoff from the basin during wet, normal and dry years.

2 Overview of Study Area

2.1 General

The study area is situated in the Balasore district of Orissa State in Eastern India (Fig. 1). It is a coastal groundwater basin bounded by the Subarnarekha River in the east, Budhabalanga River in the west, hills in the north and the Bay of Bengal in the south (Fig. 1). The basin lies between latitude 21° 27′ 0″ to 21° 45′ 45″ N and longitude 86° 56′ 15″ to 87° 20′ 30″ E covering an area of about 743 km^2. The hilly region in the northern part is the extension of the Eastern Ghats (range of mountains). The surface elevation of the area ranges from 0 to 40 m above the mean sea level. The basin mainly comprises of two rivers, the Subarnarekha and the Budhabalanga, which drain into the Bay of Bengal. The biggest river is the Subarnarekha with a catchment area of 19,300 km^2 and a length of 400 km, while the Budhabalanga River has a catchment area of 4,800 km^2 and a length of 125 km. The discharge of Subarnarekha River normally ranges from 30 to 70 m^3/s during April–May to about 4,000 m^3/s in July–August and that of Budhabalanga River varying from less than 1 m^3/s in April–May to 1,043 m^3/s in July–August. There are 14 river lift irrigation projects from the Subarnarekha River and 8 from the Budhabalanga River. There is also one lined coastal canal, which carries saline water and is used only for navigation.

2.2 Hydrometeorology

The area is characterized as sub-tropical with an annual average rainfall of 1,720 mm, of which about 80% of the total annual rainfall occurs during monsoon season (mid-June to October). On an average, there are 77 rainy days per year. During the monsoon season, a large volume of runoff from the rice fields discharges into the sea through surface drains and rivers. Thus, a substantial amount of fertile soil and applied fertilisers from the cropped fields are transported to the sea. Generally, dry year has a return period of 5 years in this region (Murty and Takeuchi 1997). The temperature rises to a maximum of 45°C in May and falls to a minimum of 7°C in January, with an average temperature of 26°C. The relative humidity is high and varies from 40% in April to 85% in August. Cyclonic storms are frequent in the study area.

The existing cropping pattern of the study area is summarized in Table 1. It can be seen from this table that 97% of the cultivable command area is under monsoon crops and 47% under non-monsoon crops. Among monsoon crops, 25% is irrigated and 75% rainfed, whereas 71% of the non-monsoon crops is under irrigation and 29% rainfed. Major crop in the monsoon season is rice. The major crop in the non-monsoon season (November to May) is also rice due to food habits, more familiarity with rice cultivation and less expensive inter-cultural operations. Rainfall contribution to the water requirement of non-monsoon rice is negligible and river lift schemes are also not adequate. Therefore, additional water

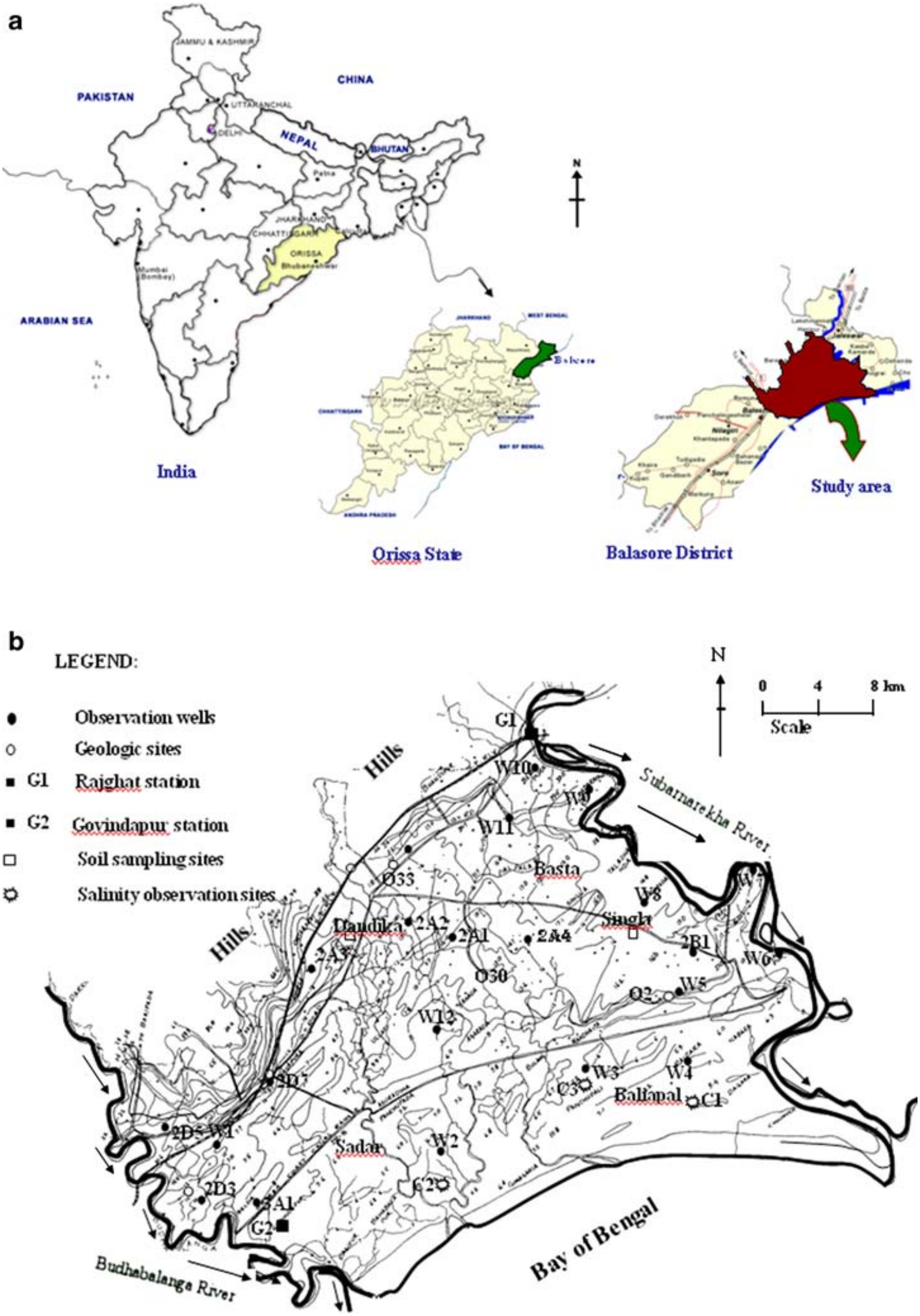


Fig. 1 Location map of the study area

Table 1 Existing cropping pattern in the study area

Crop	Irrigated area (ha)	Non-irrigated area (ha)	Total area cultivated (ha)
Paddy (M)	11,457	34,943	46,400
Paddy (NM)	7,437	NIL	7,437
Wheat (NM)	263	NIL	263
Maize (NM)	56	NIL	56
Green gram (NM)	255	2261	2,516
Black gram (NM)	164	1,967	2,131
Onion (NM)	480	NIL	480
Other vegetables (NM)	5,848	NIL	5,848
Groundnut (NM)	760	NIL	760
Mustard (NM)	393	2134	2527
Potato (NM)	271	NIL	271
Total of NM crops	15,927	6,362	22,289

M Monsoon, *NM* Non-monsoon

Source: (District Agricultural Office (Govt. of Orissa) 2000, personal communications).

requirement is met by groundwater. Both gaining and loosing stream conditions exists in the basin with time, river stage and groundwater levels.

2.3 Hydrogeologic Setup

The age of the geologic formations of the basin ranges from Archean to Quaternary. Tertiary and Quaternary formations are predominant over the basin, while the Archeans formations are prevalent near the northern boundary. The selected river basin consists of clay, fine and coarse sand with gravel deposited by the Subarnarekha and Budhabalanga rivers. The details about the hydrogeologic setting of the Balasore basin are given in Rejani et al. (2003).

3 Methodology

3.1 Overview of Visual MODFLOW

Visual MODFLOW, which integrates the MODFLOW for simulating the flow and MT3D for simulating the transport is not only a versatile and robust model for simulating groundwater flow but also used by the researchers worldwide. It is a widely used software package due to its easy access, relatively less expensive, more user friendliness and capability for simulating larger areas. MODFLOW is a modular three-dimensional finite difference groundwater flow model (McDonald and Harbaugh 1988), which simulates transient/steady groundwater flow in complex hydraulic conditions with various natural hydrological processes and/or artificial activities and, can be used for large areal extent and for multi-aquifer modelling. Hydrogeologic layers can be simulated as confined, unconfined or a combination of the two. Boundary conditions include specific head, specific flux and head-dependent flux.

MT3D (Zheng 1996) uses a modular structure similar to that implemented in MODFLOW. This model structure makes it possible to simulate advection, dispersion and sink/source mixing and chemical reactions independently without reserving computer memory space for unused options. Hence, MT3D has been used in this study to simulate the seawater intrusion process.This model uses a mixed Eularian-Lagrangian approach to the solution of three-dimensional advection-dispersion transport equation. MT3D is based on the assumption that changes in concentration field will not affect the flow field independently. This allows the user to construct, calibrate and validate a flow model independently. After the flow simulation, MT3D receives the calculated hydraulic heads and various flow terms saved by MODFLOW to set the basis for simulating and predicting the solute transport behaviour of groundwater systems. In addition to the determination of groundwater head distribution in space and time, Visual MODFLOW can calculate flow fluxes across cell boundaries. Also, there are separate modules (packages) for simulating the effect of rainfall, river, etc. Thus, MODFLOW package is very flexible and can readily coupled with other programs for optimal groundwater management. Hence, Visual MODFLOW software package was selected in the present study. Because of the lack of available data, only two-dimensional transient flow is simulated in this study.

3.2 Conceptual Model of the Balasore Groundwater Basin

The conceptual model for the study area was developed based on the surface elevation contour map, well logs at 60 sites and the information collected during field investigations (Fig. 2). An important tool to characterize the aquifer is hydrogeological profiles. The geologic profiles revealed that the basin is comprised mainly of three distinct confined/ semi-confined aquifers separated by clay layers of thickness ranging from 2 to 40 m. Of the three aquifers, the first one consists of fine sand and the remaining two consist of coarse sand with gravel. First aquifer having thickness 1–50 m exists at depth of 2–60 m. Depth to the second aquifer ranges from 30 to 70 m, with a thickness of 2 to 62 m. Third aquifer having a thickness of 5–15 m exist at depths of 40–105 m. The first aquifer is exploited by

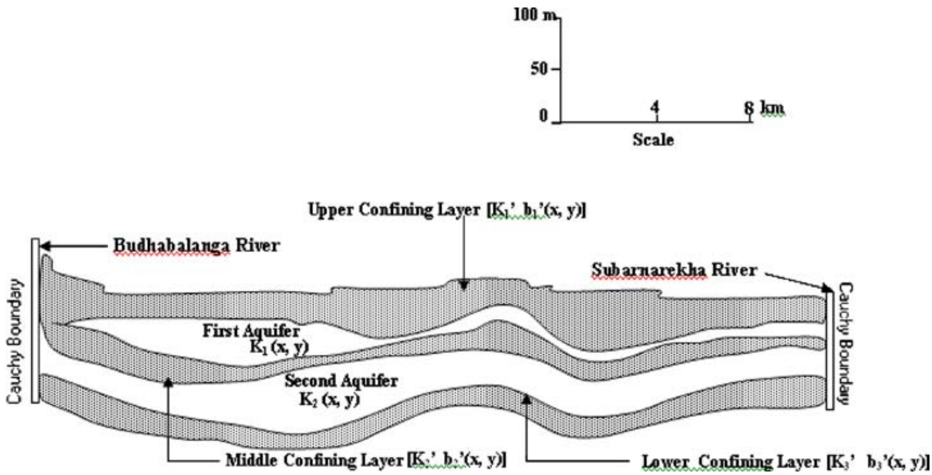


Fig. 2 Conceptual model of the Balasore aquifer (*cross-sectional view*)

low discharging dug wells for the drinking purpose, and the third aquifer is very deep and under-exploited due to high installation costs. More than 90% of the groundwater extraction is from the second aquifer. Therefore, the present study concentrates mainly on the second aquifer, which is over-exploited to meet the burgeoning irrigation demand. The aquifers are recharged by rainfall, rivers and interflow from the hills. The study area is hydraulically bounded in the south by the sea (Bay of Bengal).

Here, in this study, three types of boundaries can be considered – specified head boundaries for the sea, specified flow boundares for the upstream hilly area of Mayurbanj District and the head-flow dependent boundaries for the rivers and are described in detail in Section 3.4. In the present study, it is assumed that the hydraulic conductivities of the first and second aquifers vary along horizontal and vertical directions and the hydraulic conductivity of the aquitard is assumed as homogenous and is described in Section 3.6.1.

3.3 Discretization of the Basin

After the conceptual model was developed, the study area was discretized by dividing it into 83 rows and 92 columns. The grid spacing is 1,000 m×250 m in the non-saline zone and 125 m×250 m in the saline zone. Thus, total number of cells over the area is 3,403 each of dimension 125 m×250 m and 582 cells of dimension 1,000 m×250 m in each layer. Based on the groundwater level data availability, month was chosen as the time step within which all hydrological stresses can be assumed to be constant. Visual MODFLOW imports the data files of format ASCII or surfer.grd. Hence, the data on surface elevation, elevation of each layers, groundwater elevation and groundwater salinity were made in surfer.grd format and fed as input.

3.4 Assigning Boundary Conditions

Groundwater flow in the aquifer layers is governed by conditions at the boundaries of the groundwater basin. There are two rivers (Subarnarekha and Budhabalanga), which serve as two boundaries of the basin. As mentioned above, three types of boundary conditions have been considered: Dirichlet boundary (Bay of Bengal), Neumann boundary (upstream boundary, hilly area) and the Cauchy boundary (rivers). The flux from the upstream hilly area of Mayurbanj district was estimated by using the Darcy's equation and the modified Sichardt equation (Andres et al. 1982). It was found to range from 80 to 3930 m^3/day. The effect of flow between the rivers and aquifer was simulated by dividing the rivers into reaches containing single cells. The river bed conductance, C_{RIVER}, was computed by using the equation;

$$C_{\mathrm{RIVER}} = \frac{K_r L W_r}{B} \quad (1)$$

where, K_r = hydraulic conductivity of the river bed (m/s), W_r = width of the river (m), L = length of the reach/grid size (m), and B = thickness of the riverbed (m).

The river bed conductance of Subarnarekha River ranges from 88,962 to 41,060 m^2/day. The river bed conductance of Budhabalanga River is 34,216 m^2/day due to the narrow width of the river throughout the basin. Hence, there was no chance of seawater intrusion from places other than the sea, zero concentration was considered everywhere except the Bay of Bengal boundary.

3.5 Initial Conditions

For the reasons of data availability, April 1997 groundwater levels, groundwater salinity and river stages were used as the initial condition and 1997–1998 data were chosen to calibrate the model.

3.6 Estimating Model Parameters

The model input includes hydrogeological parameters such as hydraulic conductivity and specific storage (S_s), porosity, horizontal and vertical dispersivities and hydrological stresses like recharge, interflow, evapotranspiration, abstraction, river influence, initial and boundary conditions.

3.6.1 Hydrogeological Parameters

Samples were collected from the study area and a sieve analysis was performed at the University of Hannover, Germany. The hydraulic conductivity of the soil samples was estimated using the well-known Hazen equation (Freeze and Cherry 1979).

$$K = 0.01\, d_{10}^2 \tag{2}$$

where, K = hydraulic conductivity (m/s), and d_{10} = effective size of the soil particles (mm), determined from the grading curve.

The hydraulic conductivity of sample representing the riverbed and bank of Subarnarekha River were estimated as 1.13×10^{-3} and 2.11×10^{-6} m/s, respectively. Similarly, the hydraulic conductivity of samples from the riverbed and bank of Budhabalanga River and at two places, Dandika and Singla (Fig. 1) were estimated as 5×10^{-6}, 1.25×10^{-6}, 9.8×10^{-8} and 10^{-7} m/s, respectively. These values of hydraulic conductivity were used in the estimation of river seepage and interflow.

MODFLOW calculates transmissivity for each layer after computing the layer thickness from top and bottom elevations. Transmissivity (T) for a confined aquifer of thickness b is defined as $T=K\times b$, where K=aquifer hydraulic conductivity. The hydraulic conductivity and specific storage of the aquifers were obtained from the pumping tests conducted by the Central Groundwater Board, Orissa (CGWB 1999). The hydraulic conductivity of the first aquifer varies from 1.1×10^{-4} to 1.2×10^{-5} m/s and the specific storage from 1×10^{-3} to 1.3×10^{-4} m^{-1}, whereas the hydraulic conductivity of the second aquifer varies from 7.38×10^{-4} to 1.58×10^{-3} m/s and specific storage ranges from 1.2×10^{-4} to 4.8×10^{-5} m^{-1}. Because of the unavailability of vertical hydraulic conductivity data, vertical anisotropy was considered as 100.

Table 2 The depth and screen positions of the observation wells used for groundwater monitoring

Well no.	Depth (m)	Screen position (m)	Well no.	Depth (m)	Screen position (m)
W1	36.8	−29.0 to −36.3	2A1	45.0	(Open well)
W2	61.5	−54.0 to −61.0	2A3	37.0	(Open well)
W3	36.5	−27.5 to −36.0	2A4	15.0	(Open well)
W4	45.5	−39.0 to −45.0	2B1	16.0	(Open well)
W5	56.0	−46.0 to −55.0	3A1	21.0	(Open well)
W6	47.0	−35.5 to −46.0	2D3	15.0	(Open well)
W7	47.0	−36.0 to −45.5	O25	60.0	−30.0 to −55.0
W8	49.0	−36.5 to −48.0	O30	52.6	−30.0 to −41.0
W9	56.5	−43.5 to −55.5	O33	28.5	−15.0 to −27.0
W10	59.0	−46.0 to −57.5	2A2	71.0	−58.0 to −71.0
W11	44.0	−31.0 to −43.0	2D5	55.0	−46.5 to −54.5
W12	51.0	−41.0 to −51.0	2D7	33.0	−22.0 to −33.0

Source: (Orissa Lift Irrigation Corporation Ltd. Govt. of Orissa, India, 2000, personal communications); CGWB (1999).

The effective porosity was estimated from the graph showing the relationship between hydraulic conductivity and effective porosity (Andres et al. 1982) and was found to be 25% for the first aquifer and 25–28% for the second aquifer. To minimize the numerical dispersion, Peclet number (P_e) should be less than or equal to 1 ($P_e = \Delta l/4\alpha \leq 1$, where Δl = characteristic nodal spacing and α = characteristic dispersivity (Anderson and Woessner 1992)). Therefore, longitudinal dispersivity is taken as 125 m, which is the same as the grid length in the saline area. The transverse dispersivity was considered as 1/100th of longitudinal dispersivity (Gelhar and Axness 1983).

3.6.2 Estimation of Groundwater Recharge

Groundwater recharge consists of rainfall, flow from adjoining areas, seepage flow from drains, deep percolation from irrigated rice and non-rice areas. The recharge package in MODFLOW is designed to simulate areal distributed recharge to the groundwater system. To compute the recharge from rainfall, 25 years rainfall data (1976–2000) were collected and the recharge was calculated using the following equation (Chandra and Saxena 1975):

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

where, R = areal recharge (cm), and R_{av} = the average annual rainfall (cm).

Recharge from irrigated fields, including the losses in field channels was estimated using the guidelines suggested by the Groundwater Estimation Committee (1984), which are as follows:

(a) Recharge from irrigated rice area is about 35–64% of tubewell discharge, and
(b) Recharge from irrigated non-rice area is about 25–36% of tubewell discharge.

The different percentage of seepage and percolation in crop fields adopted were based on the studies conducted in similar areas.

Table 3 Description of management scenarios selected

Scenario	Description
Current and required pumping: scenario A	The lack of knowledge among the farmers about the gross irrigation requirement resulted in an excessive groundwater pumping. Therefore, this scenario reveal the need for optimum pumping schedule in the study area.
Normal versus dry years: scenario B	The frequency of occurrence of dry years in the region is 5 years. In order to quantify the severity of water problem during dry years, the groundwater level and salinity corresponding to normal and dry years were simulated.
Aquifer response to various pumping levels (second aquifer): scenario C	This scenario explores the response of the Balasore basin to 25% increase and 25% reduction; 50% increase and 50% reduction in the current pumping level. Thus, this scenario is expected to provide an insight into the upper limit of pumpage for existing wells.
Impact of 7 years pumpage on the second aquifer: scenario D	This scenario answers to the question 'what will be the groundwater condition after 7 years if the present trend of withdrawal continues?'
Increased withdrawal from the first aquifer: scenario E	The first aquifer is currently underexploited. Therefore, three levels of pumping, viz., 125, 150 and 200% pumping from the first aquifer are simulated to explore the possibility of increased withdrawal from this aquifer.

3.6.3 Evapotranspiration

The evapotranspiration (ET) package simulate the effects of plant transpiration via capillary rise from the saturated zone. As the aquifers under study are deep, the loss of groundwater by ET was considered negligible in this study.

3.6.4 Groundwater Abstraction

The well package of MODFLOW is designed to simulate the inflow and outflow through recharge wells and pumping wells, respectively. The residual abstraction amounts in the second aquifer were assigned to 97 well cells totalling a groundwater withdrawal of about 265.5×10^6 m^3. Each well cell represents the total pumpage from actual wells in that cell. The average pumping from tubewells located in the second aquifer ranges from 0.015 to 0.470 m^3/s and that from dug wells tapping the first aquifer varies from 0.001 to 0.010 m^3/s.

3.7 Model Calibration and Validation

The transient calibration of the developed model was done following the standard procedure (Bobba 1993; Ting et al. 1998). Because of the limited field data, the groundwater levels observed at 12 observation wells and the groundwater salinity observed in 3 wells for the 1997–2000 period were used for calibration, whereas the groundwater levels at 21 observation wells and the groundwater salinity observed in 3 wells during the 2000–2001 period was used for validation (Fig. 1). If more and more groundwater level and salinity data are available in the future, the simulation model developed for the basin could be re-

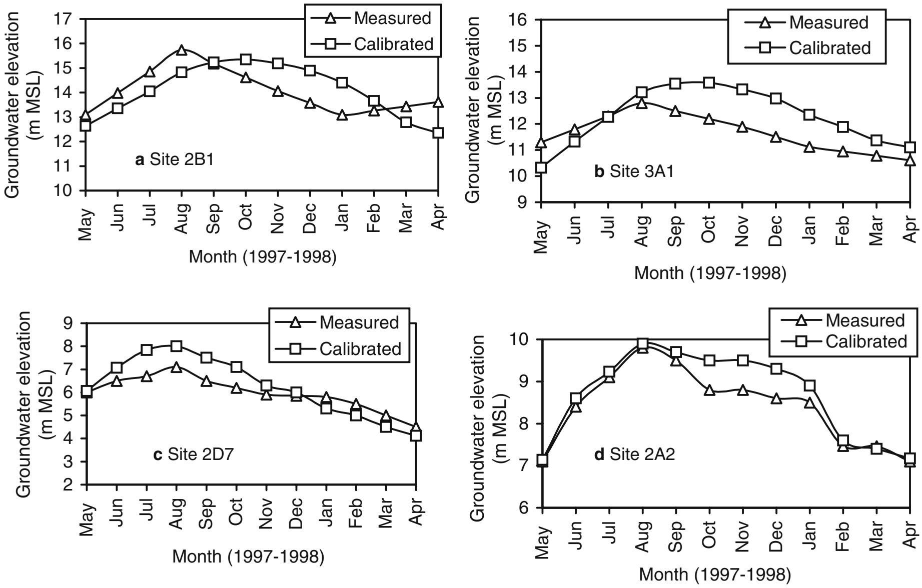


Fig. 3 a–d Comparison between simulated and measured groundwater level at Sites 2B1 and 3A1 in the first aquifer and 2D7 and 2A2 in the second aquifer

calibrated and validated for improved results, if any. The depth and screen positions of the observation wells used for calibrating and validating the model are summarized in Table 2.

Computed and measured values of groundwater levels as well as those of groundwater salinity were compared and the model parameters (horizontal and vertical hydraulic conductivities, storage coefficient) and hydrologic stresses (recharge and river seepage) were adjusted to improve the matching. The results of calibration and validation could be evaluated by means of mean error (ME) (Konikow 1977; Luckey et al. 1986; Ting et al. 1998), mean absolute error (MAE) (Ting et al. 1998), and root mean squared error (RMSE) (Kashaigili et al. 2003; Bobba 1993; Yager 1987; Ting et al. 1998). However, RMSE is generally thought to be the best measurement of error, if the errors are normally distributed. These three measures of error Eqs. 4 and 5 quantify the average error in the calibration. In this study, ME and RMSE were used.

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \tag{4}$$

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5} \tag{5}$$

where, h_m = observed groundwater level (m), h_s = simulated groundwater level (m), and n = total number of observed data.

In addition, a time series plot of measured and simulated groundwater levels, a useful way to present the results from a transient calibration (Anderson and Woessner 1992), was

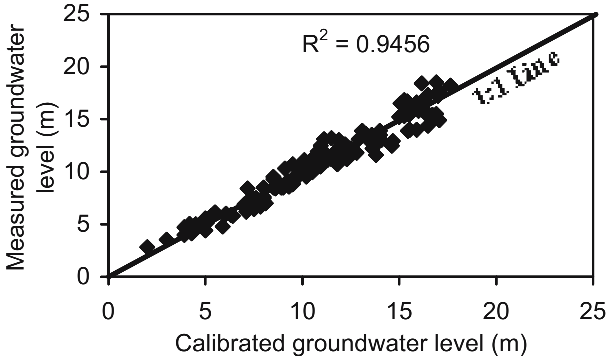


Fig. 4 1:1 plot and linear regression between measured and calibrated groundwater levels at 12 sites for the calibration period

prepared. A linear regression analysis of the measured and calibrated groundwater level was also done (Ting et al. 1998).

3.8 Sensitivity Analysis

Due to the uncertainties in estimating the aquifer parameters, stresses and boundary conditions, a sensitivity analysis is an essential step in modelling studies. This is particularly important when many parameters are to be optimised during calibration. The main objective of a sensitivity analysis is to understand the influence of various model parameters and hydrological stresses on the aquifer system and to identify the most sensible parameter(s), which will need a special attention in future studies. For the present study, the sensitivity analyses are performed for horizontal and vertical hydraulic conductivities, specific storage, interflow and river seepage. A 50% increase and decrease of the calibrated parameter/input values were assigned to assess the sensitivity (Ting et al. 1998).

Table 4 Results of model calibration

Site	Calibration period (1997–1998)	
	ME (m)	RMSE (m)
3A1	−0.63	0.98
2D3	−0.34	1.58
2B1	0.02	0.89
2A4	0.68	1.66
2A3	−4.08	4.25
2A1	−1.42	1.68
2A2	−0.27	0.38
2D5	0.19	0.70
2D7	−0.27	0.66
O25	−0.80	1.15
O30	0.23	0.48
O33	−0.03	0.53

Table 5 Results of model validation

Site	Validation period (2000–2001)				
	ME (m)	RMSE (m)	Site	ME (m)	RMSE (m)
3A1	0.23	0.41	W3	−1.33	1.76
2D3	0.17	0.26	W4	0.36	0.91
2B1	0.40	0.53	W5	0.06	0.73
2A4	0.58	0.68	W6	0.33	0.80
2A3	−1.39	2.01	W7	0.71	0.81
2A1	−1.40	1.60	W8	1.87	1.94
2A2	0.23	0.41	W9	0.02	0.28
2D5	2.12	3.36	W10	0.28	0.98
2D7	0.47	1.06	W11	0.28	0.78
W1	0.68	0.73	W12	−0.09	0.66

3.9 Simulation of Salient Pumping Strategies

The calibrated and validated model could now be used for a variety of management and planning studies. In a predictive simulation, the parameters optimized during calibration are used to predict the system response to future events. Predictive simulations were performed to minimize the overexploitation in the second aquifer. In this study, the region north of the coastal canal is called “upstream” and the region south of the coastal canal is called “downstream.” Five management scenarios (Table 3) were simulated.

4 Results and Discussion

4.1 Calibration and Validation Results

Results of the model calibration are presented in Fig. 3a–d, which show that the calibrated values reasonably match with the observed ones. A scatterplot (1:1 plot) and a regression analysis of the measured groundwater level against the calibrated head are illustrated in Fig. 4 which can be safely considered to be a reasonable fit between these two data sets (R^2= 0.94). Further, Tables 4 and 5 reveal that the mean error (ME) and root mean square error (RMSE) for almost all the sites during calibration and validation are reasonably low and are within acceptable limits. Almost similar calibration results were obtained for the other two years also. The observation well 2A3 lies in the downstream of Mayurbunj hills, and is most likely to be influenced by the interflow from the hills. As a result, the average differences between measured and simulated groundwater levels are relatively high. After calibration, the vertical hydraulic conductivity of the aquifers was found to 1/10th of the horizontal hydraulic conductivity. The calibrated horizontal hydraulic conductivity of the first and second aquifers was found to range from 4.32 to 7.78 m/day with a storage coefficient of 0.0004. The recharge in the first aquifer was calibrated as 26% of the annual rainfall. The simulated value of salinity was also found to match with few observed values available at the three sites.

4.2 Sensitivity of Analysis

The sensitivity of model parameters was analyzed by a 50% increase/decrease in horizontal and vertical hydraulic conductivities, storage coefficient, interflow, recharge and river seepage. The results of the sensitivity analysis are depicted in Fig. 5a–d. It is obvious from these figures that the first aquifer is more sensitive to recharge and river seepage at all the sites except in the middle of the basin (Site 2A1), which is sensitive only to recharge. The second aquifer is sensitive to interflow and river seepage (near the river). The interflow is the most sensitive parameters and stress factors for the basin and is sensitive to hydraulic conductivity at almost all sites except W11 and W12. Even though the Site W8 is more sensitive to interflow, it is also sensitive to vertical hydraulic conductivity as well as storage coefficient.

4.3 Simulating Salient Pumping Strategies

(1) Scenario A: current and required pumping

The results of the groundwater simulation under present pumping condition are shown in Fig. 6. It is apparent from Fig. 6 that under the present pumping conditions, the groundwater levels in most wells located in the downstream region (i.e., saline zone) lie 2 m below the MSL during dry periods. It was also found that by replacing the present pumping with the required pumping, the groundwater condition improves significantly; groundwater levels only in few wells located in the saline zone lie 2 m below the MSL during dry seasons. It is also discernible that in the saline tract of the second aquifer, the groundwater flow direction reverses (i.e., seawater flows towards inland) during the non-monsoon season under the present pumping pattern, whereas in the monsoon season, the groundwater condition improves significantly, and the groundwater flow is towards the Bay of Bengal (Fig. 7a,b). It should be noted that, there is no reverse flow even during the non-monsoon season in the first aquifer.

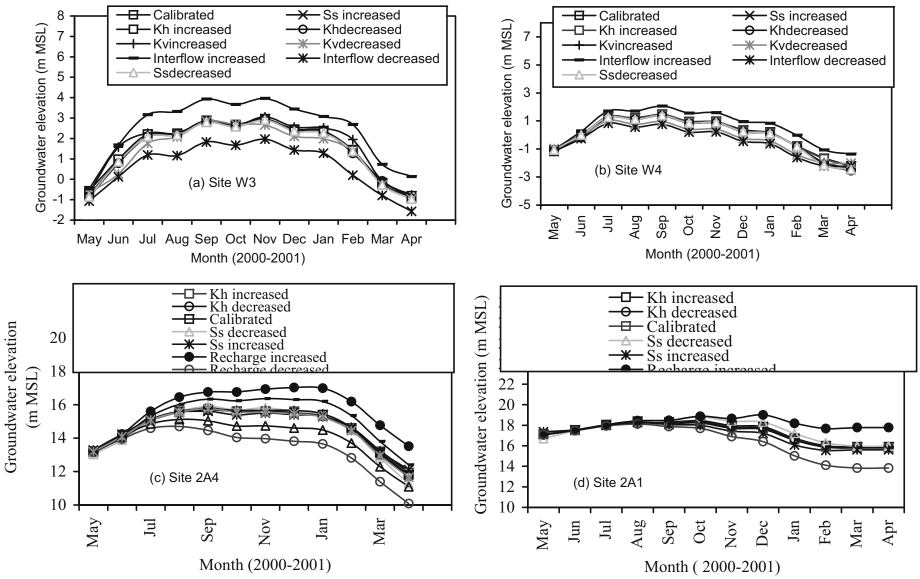


Fig. 5 a–d Sensitivity analysis at Sites W3, W4, 2A4 and 2A1

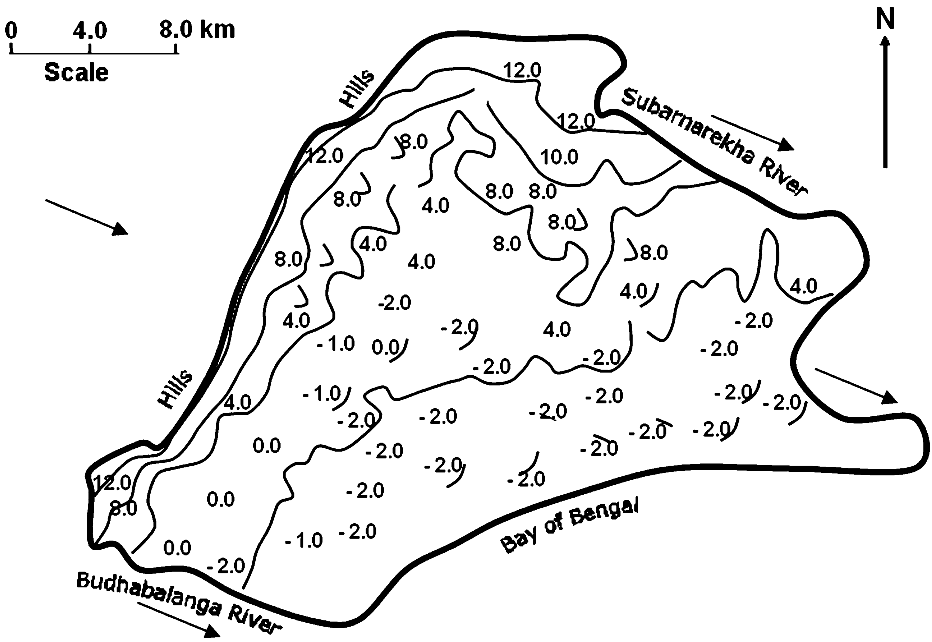


Fig. 6 Groundwater scenario (*non-monsoon season*) under present pumpage conditions

It can also be seen that compared to the current pumpage, the required pumpage with present cropping pattern can result in an increase in groundwater levels at Sites W3, W4, W7, W11 and W12 by 0.3, 1.3, 0.5, 1.1 and 0.4 m, respectively (Fig. 8a–e). Therefore, rescheduling the current pumping can result in a better groundwater condition for the region. The groundwater levels at Sites W3 and W4 (below MSL) under current pumpage conditions (Figs. 6 and 8a,b) indicate that the downstream region is the worst affected, and hence some remedial measures are essential. The groundwater contours in the wet year with present cropping pattern indicates that the groundwater levels in all the wells even in the saline area lie above the MSL. It may be due to the reduction in pumping and/or due to the increased groundwater recharge. Thus, there is a good scope for reducing the seawater intrusion by reducing the pumping and recharging the interfacing area. Furthermore, the water demand in the downstream can also be met by the exploiting the upstream region (the region having the least drawdown) and transporting the water to the downstream region or by changing the non-monsoon cropping pattern in the downstream region.

The groundwater salinity contours ranging from 35,000 to 250 mg/l under existing pumping conditions. About 5 km width of the coastal track is affected by seawater intrusion. Thus, Scenario A indicates that the second aquifer is threatened by seawater intrusion. Hence, either by recharging the aquifer in this region or the rescheduling of present pumpage is required urgently to minimize further encroachment of freshwater aquifer by seawater intrusion.

(2) Scenario B: normal versus dry years pumping

The groundwater contours corresponding to dry year pumping as shown in Fig. 9 indicates that at some wells in the saline region, the groundwater levels have declined even 4 m below the MSL during the dry period. The temporal variation of groundwater levels at

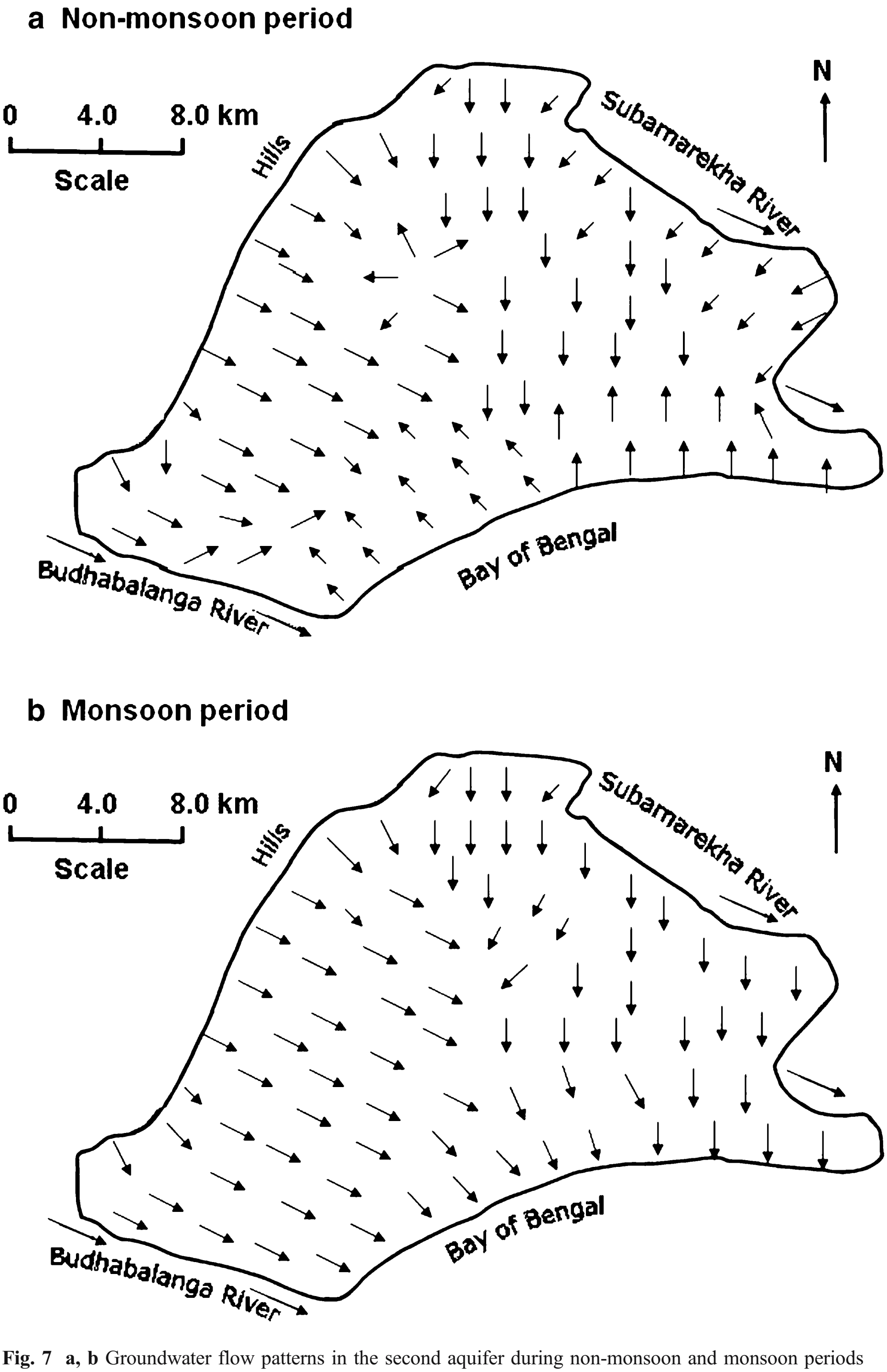


Fig. 7 **a, b** Groundwater flow patterns in the second aquifer during non-monsoon and monsoon periods

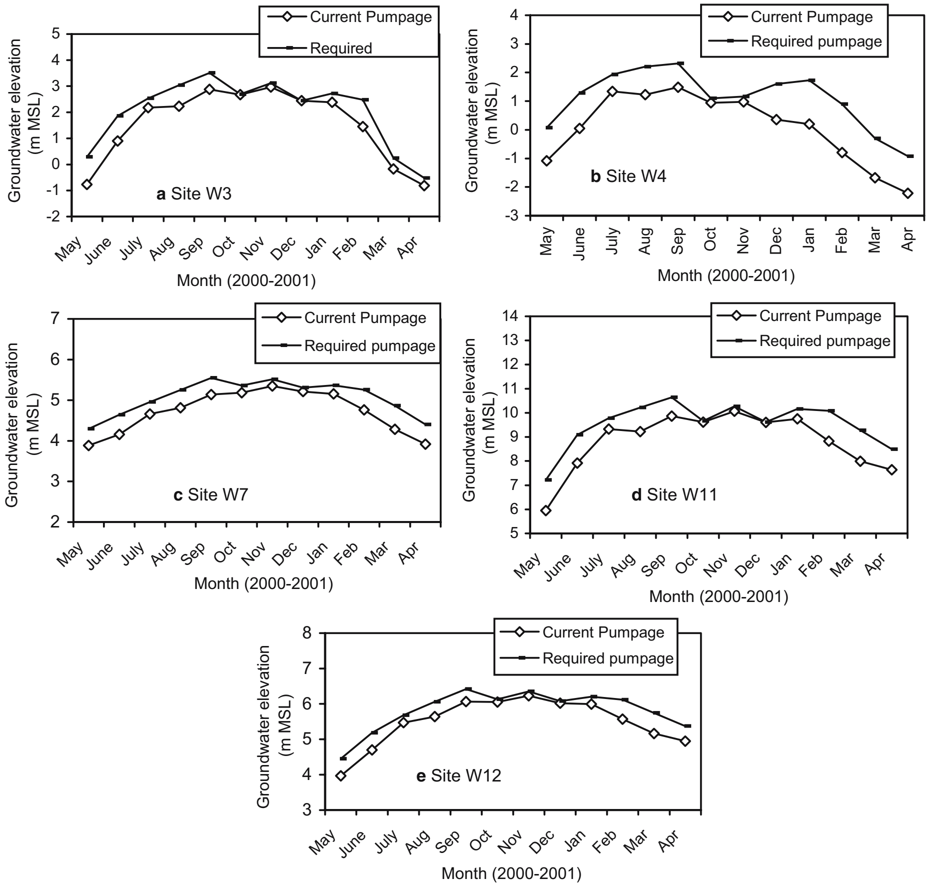


Fig. 8 a–e Temporal variation of groundwater levels at five sites under current and required pumping conditions

sites W4, W8, W11 and W12 in dry and normal years under required pumpage conditions is shown in Fig. 10a–d. Even at Site W8, which is near to the river, the net decline in groundwater level (relative to May 2000) is 0.6 and 2.0 m in normal and dry years. However, the groundwater elevation at Sites W3 and W4 during normal and dry years is 0.9 and 1.8 m below the MSL, respectively. Therefore, some remedial measures like reducing the pumping, recharging using injection wells or changing the cropping pattern in the region south of the coastal canal is essential. Similarly, at Site W11, the net rise in groundwater level (relative to May 2000) is 1.3 m in the normal year, while it drops by 0.4 m in the dry year. Also, at Site W12, the net rise in groundwater level is 0.9 m in the normal year and no decline in the dry year. Thus, it may be possible to supply the excess groundwater from the locations having greater pumping potential like Site W11 and W12 (the upstream region) to meet a part of the water demand at the locations deficient in groundwater (the downstream region). Such an operation policy appears to be quite attractive for the long-term and sustainable utilization of the scarce water resource in the basin. However, this will require a provision of water transmission facilities.

From Fig. 11a–c, it can be seen that there is a decline of salinity in the rainy season and a rise of salinity in the critical period. These simulation results depict that the inward

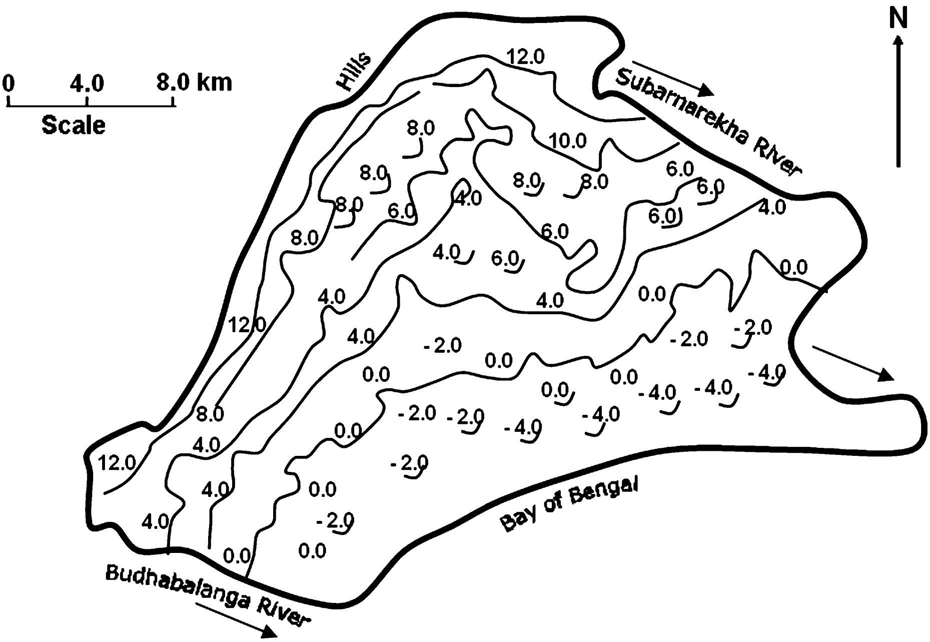


Fig. 9 Groundwater contour map (*non-monsoon period*) for the dry year under present pumping conditions

movement of saltwater front during the critical period is more than the outward movement of the front in the monsoon season. Thus, the seawater intrusion problem may aggravate in the future. Dry year pumping results in the lowering of groundwater levels, which in turn produces severe salinity as shown in Fig. 11a–c. The net increase in the salinity of dry year over a normal year under required pumping conditions is 30, 357 and 450 mg/l at sites C1, C2 and C3, respectively. It can also be seen from Fig. 11a–c that in a normal year under required pumping conditions, the net rise in salinity level is very less. Thus it is clear from Scenario B that the decline in groundwater levels and the increase in salinity of the second aquifer are severe in dry years. Therefore, controlled pumpage or groundwater augmentation by artificial recharge is very essential to save the aquifer from seawater intrusion especially in dry years as well as to ensure long-term sustainability of groundwater resources in the study area.

(3) Scenario C: response of the second aquifer to various pumping levels

Groundwater scenario (groundwater level and salinity at different sites) for 50, 75, 100, 125 and 150% of the required pumpage with present cropping pattern is shown in Figs. 12a–e and 13a–c. Compared to 100% pumpage, 150% pumpage reduced the groundwater level at Sites W4, W7, W8, W11 and W12 by 3.3, 0.5, 0.7, 0.7 and 0.6 m, respectively, and increased the salinity at Sites C1, C2 and C3 to 987, 2,120 and 5,990 mg/l, respectively. Similarly, 125% pumpage reduced the groundwater level (relative to 100% pumpage) at Sites W4, W7, W8, W11 and W12 by 1.9, 0.3, 0.3, 0.3 and 0.2 m, respectively, and increased the salinity at Sites C1, C2 and C3 to 970, 2050 and 5930 mg/l, respectively, at the end of one-year simulation.

On the other hand, the 75% pumpage increased the groundwater level (relative to 100% pumpage) at Sites W4, W7, W8, W11 and W12 by 0.2, 0.2, 0.3, 0.3 and 0.2 m,

Fig. 10 **a–d** Temporal variation of groundwater levels at Sites W3, W8, W11 and W12 during normal and dry years

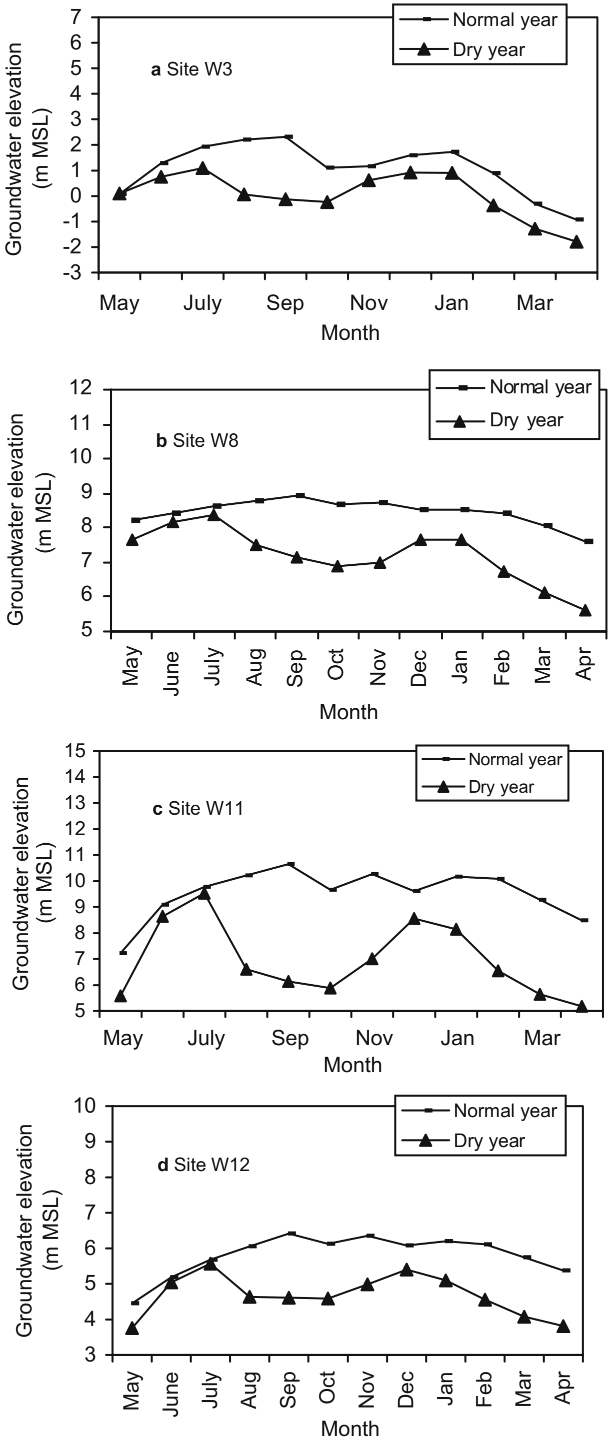
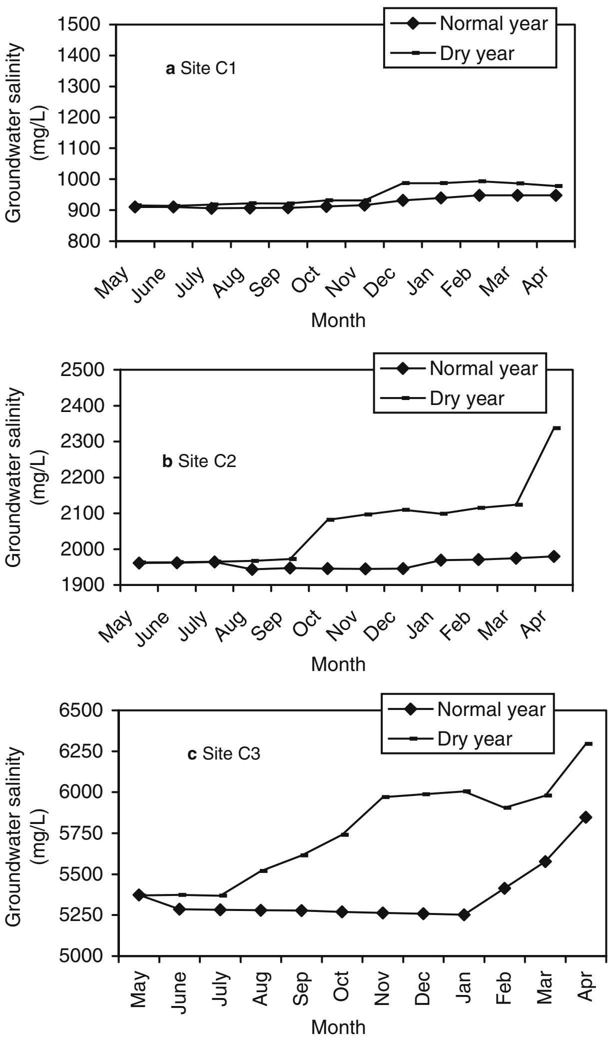


Fig. 11 a–c Temporal variation of groundwater salinity at Sites C1, C2 and C3 under current and required pumping conditions



respectively, and reduced the salinity at Sites C1, C2 and C3 to 935, 1980 and 5550 mg/l, respectively. Similarly, the 50% pumpage (relative to 100% pumpage) increased the groundwater level at Sites W4, W7, W8, W11 and W12 by 1.2, 0.5, 0.6, 0.6 and 0.4 m, respectively, and reduced the salinity at Sites C1, C2 and C3 to 925, 1,960 and 5,240 mg/l, respectively. Even 150% pumpage resulted in a rise of the groundwater level (relative to May 2000) at Sites W11 and W12. At Site W4, 50% pumpage resulted in an increase in groundwater elevation above the MSL. According to Todd (1980), the groundwater quality at Sites C2 and C3 can be categorized as 'unsuitable' (TDS>1,920 mg/l) for irrigation throughout the year. The groundwater quality at Site C3 is 'suitable' throughout the year in the present scenario. The groundwater salinity at Sites C2 and C3 can be controlled by reducing the pumping to 75 and 50%, respectively. It is obvious that there is a possibility of 100–150% exploitation in the upstream region and 50–75% in the saline area to sustain groundwater utilization in the basin.

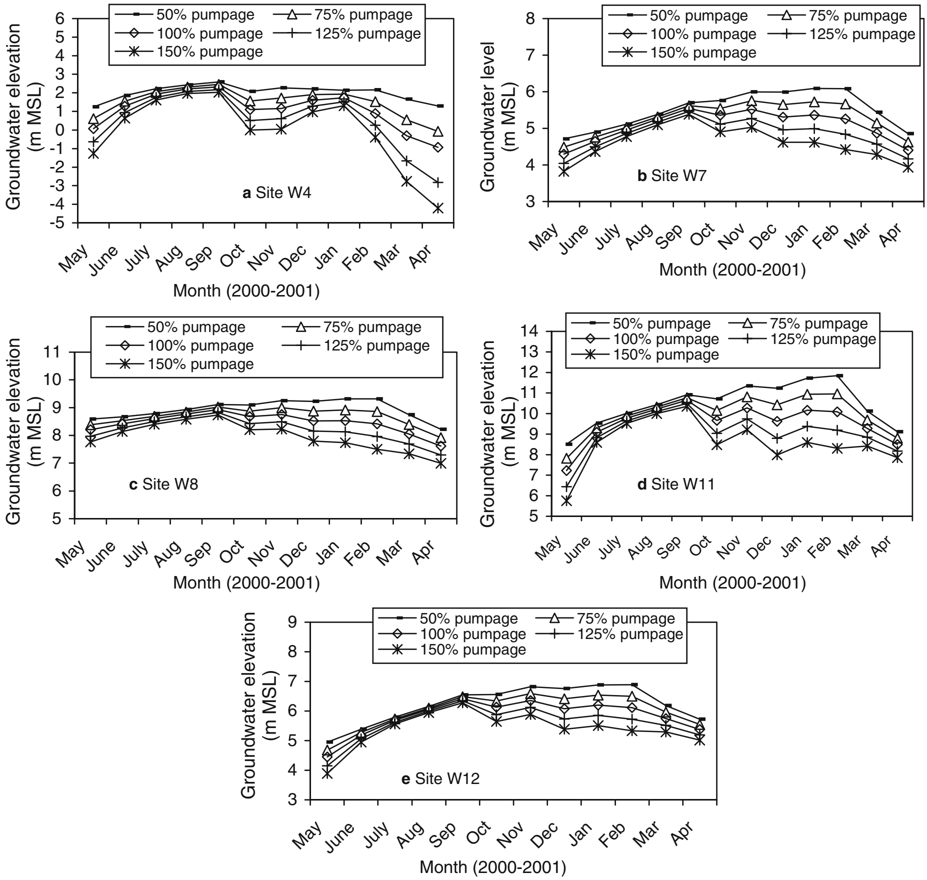


Fig. 12 **a–e** Temporal variation of groundwater levels at Sites W4, W7 and W8, W11 and W12 under 50, 75, 100,125 and 150% pumpage conditions

(4) Scenario D: groundwater conditions after 7 years under present pumpage conditions

Figure 14 shows the groundwater elevation at the end of 7 years. Under this scenario, the pumping schedule was adopted based on the assumption of one dry year in a 5-year period. It can be seen from the figure that continuation of the present pumping may reduce the groundwater elevation from −2.2 to −6.2 m at Site W4 and from 7.6 to 3.8 m at Site W8. The hydraulic gradient in the downstream portion of the basin reverses during March–April (dry period) resulting in a landward movement of seawater from the Bay of Bengal. This scenario highlights the severity of the overdraft especially in the downstream of the basin (near Site W4). Therefore, unless some artificial recharge schemes are implemented in the basin, it is recommended that the pumping rate during dry year for the existing wells tapping the second aquifer should be controlled.

(5) Scenario E: increased withdrawal from the first aquifer

The drawdown corresponding to three levels of pumping in comparison to the required pumping under scenario E is shown in Fig. 15a–c. Since April–May is the critical period,

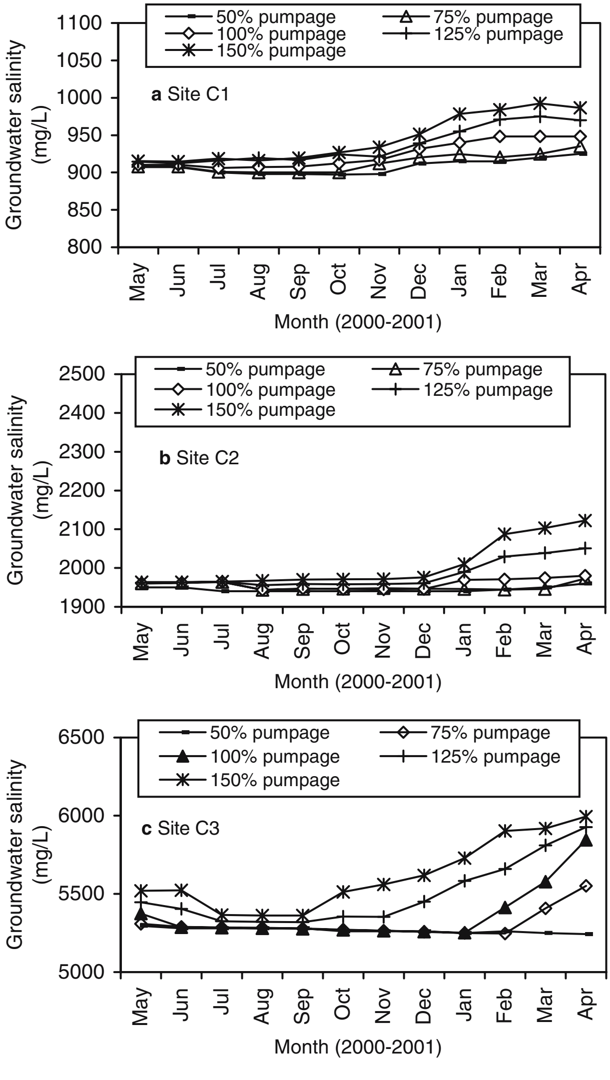
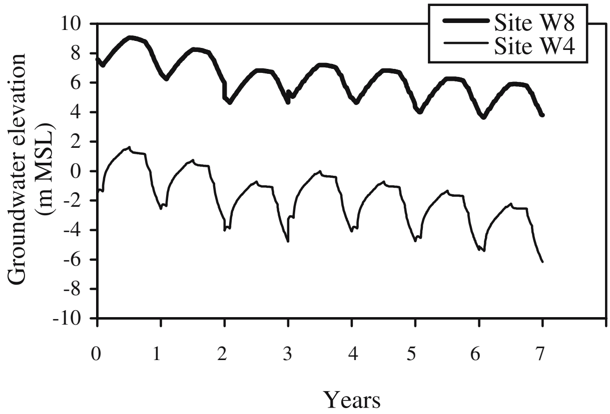


Fig. 13 a–c Temporal variation of groundwater salinity at Sites C1, C2 and C3 under 50, 75, 100, 125 and 150% pumpage conditions

the drawdowns in different months in the first aquifer have been calculated with respect to groundwater level in April month. i.e., drawdown in May is equal to the groundwater level in April minus groundwater level in May for a given pumpage. It is to be noted that125, 150 and 200% pumping produced drawdowns of 0.4, 0.87 and 1.81 m at Site 3A1; 0.06, 0.37 and 0.8 m at Site 2D3; and 2.41, 3.44 and 5.5 m at Site R1, at the end of April. It is apparent that increased pumping can cause appreciable drawdowns only at Site R1 (downstream region) in the first aquifer. The simulation results at site 2D3 under this scenario suggest a possibility of 200% pumping in first aquifer at locations near to the rivers. Also, the drawdown at Site 2B1 suggests that pumping in the upstream can be increased to 150% without any deleterious effects.

Fig. 14 Predicted groundwater fluctuation for the 7 years



(6) Groundwater conditions under promising management strategy

Finally, the most promising management strategy (based on Scenarios C and E) could be to reduce the pumpage in the downstream of the second aquifer by 50% and to increase the pumpage of the first and second aquifer at potential locations in the upstream region to 150%. The temporal variation of groundwater elevation at Site W4 shows that compared to 100% pumpage, 50% pumpage in the downstream of the second aquifer increased the groundwater elevation at Site W4 by 1.54 m (Fig. 16). From Fig. 17, it is also clear that the groundwater contours in the saline area has improved significantly; groundwater level is above the MSL almost everywhere. However, it is to be noted that the additional water demand of the downstream region can be met from the first and second aquifers in the upstream region by increasing its pumpage to 150% without any undesirable effects.

This scenario is easily acceptable in the present situation, but it requires proper water transmission facilities in the basin. The improved groundwater condition can also be obtained by adopting less water exhaustive crops, which are having more market value. For example, chilli, green gram, mustard etc. More exact values of duration of pumpage can be obtained by field tests such as step drawdown pumping test.

5 Conclusions

The Balasore coastal groundwater basin in Orissa, India is threatened by overdraft and seawater intrusion. The overexploitation is severe during the critical period (March and April) due to excessive pumping for rice cultivation. In this study, an attempt was made under limited data conditions to analyze the response of the coastal aquifer subject to various pumping levels using Visual MODFLOW. A two-dimensional groundwater flow and transport model of the basin was developed, which was calibrated and validated satisfactorily. Based upon the simulation results, the following conclusions and recommendations could be made for the study area:

- As the second aquifer is threatened by seawater intrusion, rescheduling of present pumpage is required urgently to minimize further freshwater encroachment by seawater intrusion.

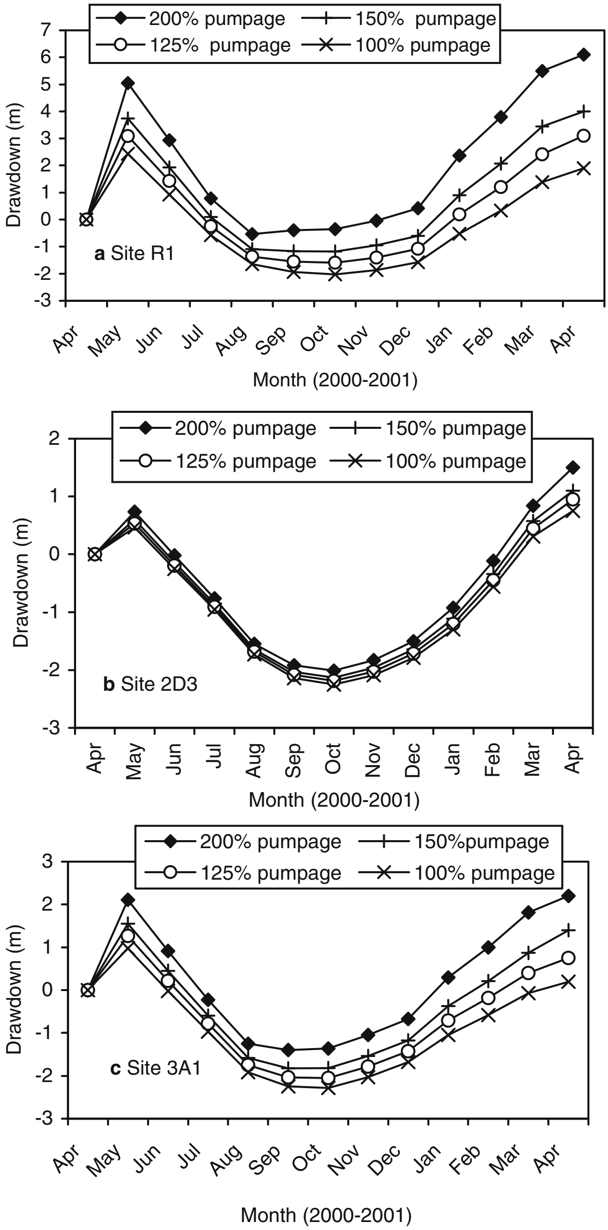


Fig. 15 a–c Temporal variation of drawdown at Sites R1, 2D3 and 3A1 due to 125, 150 and 200% pumping

- The reduction in pumping from the second aquifer and/or artificial recharge is very much essential to avoid seawater intrusion especially in dry years as well as to sustain groundwater resources on a long-term basis.
- The results of sensitivity analysis revealed that the aquifer is more susceptible to interflow and river seepage than horizontal and vertical hydraulic conductivity and specific storage.

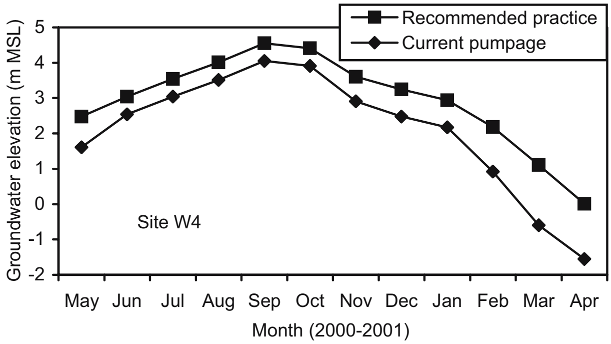


Fig. 16 Temporal variation of groundwater elevation at Site W4 of the second aquifer during non-monsoon season for the most recommended management practice

- It is viable to withdraw 100–150% groundwater in the upstream region and 50–75% in the downstream region of the second aquifer to ensure sustainable groundwater utilization in the basin without adopting any expensive measures.
- Scenario D highlights the severity of the overdraft especially in the downstream of the basin (near Site W4), which can occur in future (after 7 years) due to the continuation of the present pumping schedules. Therefore, unless some artificial recharge schemes are implemented in the basin on a regular basis, it is recommended that at least cutback in pumping from the second aquifer during dry years should be done.
- There is a possibility of 200% pumping in first aquifer at locations near to the rivers and 150% at other potential sites in the upstream region of this aquifer without any deleterious effects.

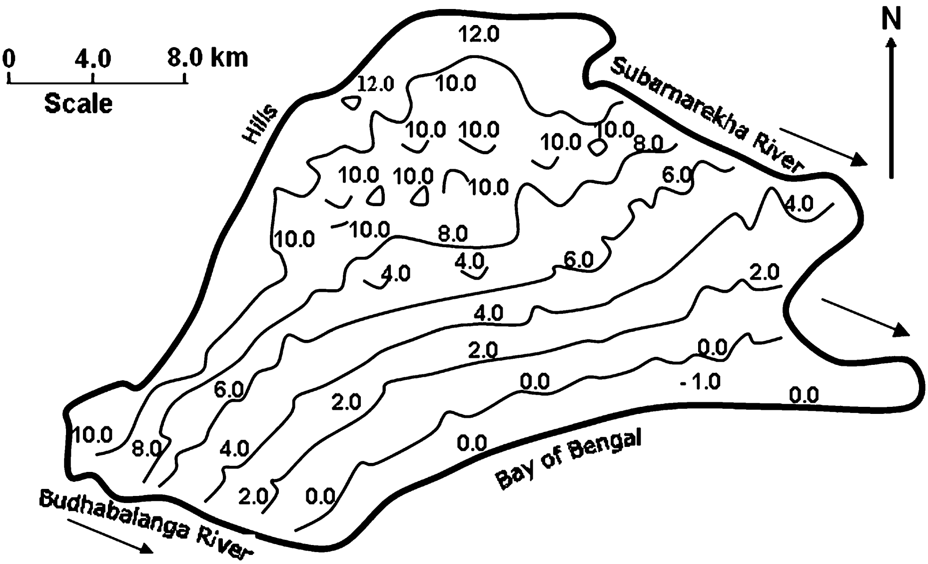


Fig. 17 Groundwater scenario of the second aquifer during non-monsoon season for the most recommended management practice

- Lastly, the most promising management strategy for the Balasore basin (based on Scenarios C and E) could be: a reduction in the pumpage from the second aquifer by 50% in the downstream region and an increase in the pumpage to 150% from the first and second aquifer at potential locations.

Therefore, unless some artificial recharge schemes (e.g., on-farm reservoirs and recharge wells) are implemented in the basin, it is recommended that the pumping rate of existing wells in the second aquifer during dry years be controlled. Future studies in this direction can be taken up by comparing the deterministic and stochastic approaches for groundwater modeling for the Balasore basin.

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