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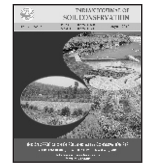

Numerical analysis of a deltaic aquifer system for sustainable management of groundwater

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ABSTRACT

In recent years, groundwater simulation models have emerged as a preferred tool of water resources managers for addressing questions about the impacts of groundwater development and the effects of human activities on ground water. The present study refers to the development of a groundwater flow simulation model along with sensitivity and scenario analysis for a deltaic aquifer in Eastern India using finite difference-based numerical model named Visual MODFLOW. The study area is a river island located in the Mahanadi delta of Odisha and is surrounded by Kathajodi River and its branch Surua. Calibration and then validation of the flow model was performed satisfactorily with a mean r value of 0.958, mean RMSE value of 0.632 and mean NSE value of 0.914. The sensitivity analysis of the model showed that groundwater level was more sensitive to river stage followed by recharge and hydraulic conductivity whereas it was least sensitive to changes in specific storage. Using the calibrated and validated numerical model, scenario analyses were done to study the aquifer response to different stress conditions. The scenario analysis indicated that there will be no significant change in the groundwater level of the study area even after 15 years of pumping at the present rate under existing conditions. The developed model can serve as an effective tool for developing strategies for sustainable water management under changing climatic and socio-economic conditions.

1. INTRODUCTION

The unique qualities of groundwater that it is generally free from pathogens, easily accessible and free from suspended particles have made it the most important and preferred source of water supply for agricultural, domestic and industrial uses. Owing to its several inherent qualities as well as the relative ease and flexibility with which it can be tapped, it has been used as and considered to be a reliable and safe source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries (Foster *et al.*, 2000; Bocanegra *et al.*, 2005). However, with worldwide aquifer depletion and growing pollution of groundwater, sustainable management of groundwater resources has become a serious challenge (Hiscock *et al.*, 2002; Sophocleous, 2005). To achieve this, it is important to understand the behavior of an aquifer system subjected to artificial stresses; and numerical models are effective tools for such studies. These days, the numerical groundwater models have emerged as a suitable choice among water resources researchers and planners for addressing questions about the impacts of groundwater development (Anderson and Woessner, 1992; Rushton, 2003). Groundwater system being highly complex and dynamic in nature, numerical models plays an important role in analyzing complex groundwater systems. These models are useful in simulating groundwater flow scenarios under different management options and thereby taking corrective measures for sustainable water resources management. In last few decades, numerical ground water simulation models have been widely used for understanding groundwater-flow dynamics and developing groundwater management strategies in different parts of the world (*e.g.* Ting *et al.*, 1998; Sophocleous *et al.*, 1999; Reeve *et al.*, 2001; Lin and Medina, 2003; Sarwar and Eggers, 2006; Zume and Tarhule, 2008; Ahmed and Umar, 2009; Al-Salamah *et al.*, 2011; Elango *et al.*, 2012; Mohanty *et al.*, 2013; Izady *et al.*, 2015; Woodward *et al.*, 2016). However, in developing countries, basin-scale groundwater modeling studies are scanty probably owing to the limited or absence of good-quality spatial and temporal field data and the lack of technical expertise.

The groundwater development over different parts of India is not uniform; it is quite intensive in some parts of the country (Mall *et al.*, 2006; CGWB, 2011). Excessive groundwater exploitation has led to alarming decrease in groundwater levels in several parts of the country such as Rajasthan, Punjab, Haryana, Tamil Nadu and Karnataka (CGWB, 2011). In India, roughly 52% of irrigation consumption across the country is extracted from groundwater, and therefore is an alarming situation with a decline in groundwater in the country (Gosain *et al.*, 2006; Jha and Chowdary, 2007). Therefore, optimum/efficient use of surface and groundwater resources is required as part of sustainable land and water resources management strategies.

In the present study, development of groundwater flow simulation model using a physically based model has been done in a river basin of Eastern India in order to understand the dynamics of groundwater flow and develop management strategies for optimal groundwater utilization. Although several software packages are available for groundwater flow simulation, in this study Visual MODFLOW has been used. Visual MODFLOW has been a widely used software package due to its easy access, more user friendliness and capability for simulating larger areas (Varni and Usunoff, 1999; Kashaigili *et al.*, 2003). For this, a study area Kathajodi-Surua Inter-basin was selected within the Mahanadi deltaic system of Eastern India.

2. MATERIALS AND METHODS

Study Area

The study area which is locally called as Bayalish Mouza is a typical river island within Mahanadi deltaic system of Eastern India and is surrounded on both sides by the Kathajodi river and its branch Surua (Fig. 1). It is located between 85°54'21" to 86°00'41"E longitude and 20°21'48" to 20 °26'00"N latitude. The total area of the river island is 35 km^2. The study area has a tropical humid climate with an average annual rainfall of 1650 mm, of which 80% occurs during the period from June to October. Agriculture is the major occupation of the inhabitants and groundwater is the major source of irrigation in the area. Groundwater is also used for water supply for domestic purposes in

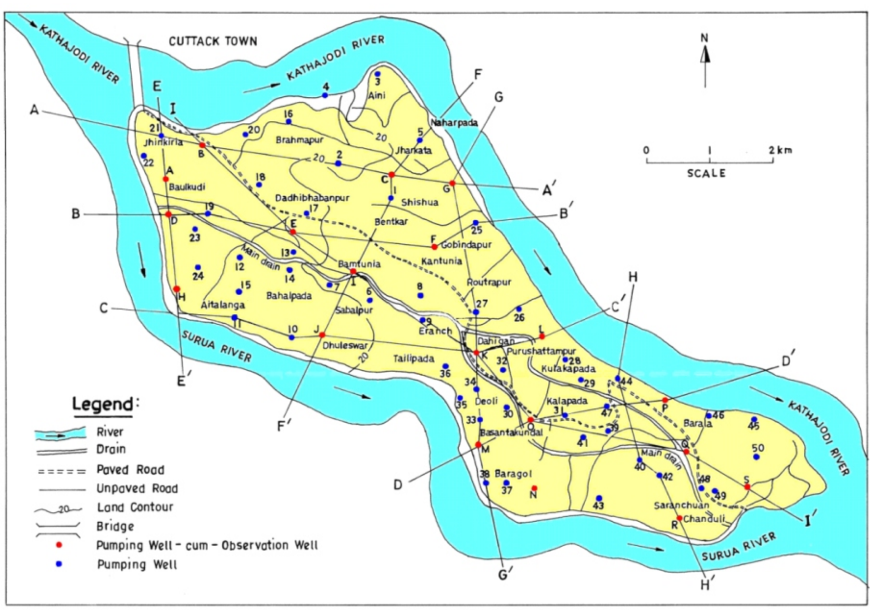

Fig. 1. Location of observation and pumping wells and geologic cross sections in the study area

the region. There are 69 functioning government tube wells in the area, which constitute major sources of groundwater withdrawals for irrigation. These tube wells were initially constructed and managed by the Odisha Lift Irrigation Corporation (OLIC), Government of Odisha, India. Now, they have been handed over to the local water users' associations. There is no water shortage during the monsoon season in the study area, but in the summer season, the farm ponds dry up and the groundwater from tubewells is not sufficient to meet the entire water requirement of the farmers.

Input Data for Modeling

Daily rainfall data of 20 years (1990-2009) were collected from a nearby meteorological observatory at ICAR-Central Rice Research Institute (CRRI), Cuttack, Odisha located at about 2 km from the study area. The drillers log chart available at 70 different sites spread over the study area were collected from OLIC office, Cuttack, Odisha. The log charts were analyzed by drawing geologic profiles and performing stratigraphic analysis across different cross-sections to characterize the subsurface formation. The analysis showed that the river basin is underlain by a confined/ 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. Pumping tests were conducted at 9 sites distributed over the study area to determine hydraulic conductivity and specific storage values. The detailed hydrogeologic investigations of the study area are presented in Mohanty *et al.* (2012).

Since no groundwater data were available in the study area, a groundwater monitoring program was initiated by the authors. Monitoring of groundwater levels in the study area was done by selecting nineteen tubewells in such a way that they represent approximately four west-east and four north-south cross-sections of the study area (Fig. 1). Weekly groundwater-level data at the nineteen sites was monitored from February 2004 to October 2007, which was used for studying the groundwater characteristics in the study area and eventually for calibration of groundwater-flow simulation model. The river stage data at 10 sections were monitored on a monthly basis and were used for assigning boundary conditions for the groundwater-flow simulation model. The river bed conductivity at 10 varied locations of the river reach was measured in laboratory by analyzing the collected core soil samples.

Overview of Visual MODFLOW

Visual MODFLOW, which integrates the MODFLOW for simulating the flow, MODPATH for calculating advective flow pathlines, MT3D/RT3D for simulating transport and SEAWAT for simulating coupled flow and transport processes is a versatile and robust model for simulating groundwater flow and transport processes. It has been used by several researchers and scientists worldwide (e.g., Ting *et al.*, 1998; Varni and Usunoff, 1999; Wilsnack *et al.*, 2001; Kashaigili *et al.*, 2003; Fleckenstein *et al.*, 2006; Zume and Tarhule, 2008; Ajami *et al.*, 2011; Mohanty *et al.*, 2013; Izady *et al.*, 2015; Woodward *et al.*, 2016). MODFLOW is a modular three-dimensional finite difference groundwater flow model, 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 modeling (McDonald and Harbaugh, 1988). Visual MODFLOW is the well recognized standard groundwater model used by various regulatory agencies, universities, consultants and industry both in developed and developing countries.

Governing Equation for Groundwater Flow

Based on the hydrogeologic investigations of the study area, a three-dimensional groundwater flow model was used for simulating flow in the confined aquifer under study. The Visual MODFLOW uses following governing equation for simulating transient groundwater flow in the heterogeneous and anisotropic confined aquifer (Anderson and Woessner, 1992):

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial}{\partial z}) \pm W = S_s \frac{\partial h}{\partial t} \quad ...(1)$$

Where, K_x, K_y, and K_z = aquifer hydraulic conductivities in x, y and z directions, respectively [LT^{-1}]; h = hydraulic head, [L]; W = volumetric flux per unit volume representing sources and sinks of water in the aquifer system ('+' for source and '-' for sink), [T^{-1}]; S_s = specific storage of the aquifer, [L^{-1}]; and t = time, [T].

System Conceptualisation and Model Development

A key step in groundwater modeling is to conceptualize the system being modeled. The purpose of building a conceptual model is to simplify the complex field problem and organize the associated field data to make it amenable to modeling (Anderson and Woessner, 2002; Rushton, 2003). The nature of the conceptual model determines the dimensions of the numerical model and the design of the grid. Based on the hydrogeologic investigations, the study area was conceptualized as a two-layer system with the lower one representing the confined aquifer and upper one representing the semi-confining layer. The details of the conceptual model of the study area have been presented in Mohanty *et al.* (2013). This conceptual model provided a basis for the design and development of a numerical model of the study area using Visual MODFLOW software.

The numerical model was discretized into 40 rows and 60 columns using the Grid module of Visual MODFLOW software (Fig. 2). This resulted in 2400 cells, each with a dimension of approximately 222 m 215 m. The data on surface elevation, bottom elevation of the top layer, bottom elevation of the aquifer, the location of pumping wells, location of observation wells and weekly groundwater levels of the model period were imported to the MODFLOW software. The details of the model development including the assignment of boundary conditions, initial conditions and model parameters are described in Mohanty *et al.* (2013).

Calibration and Validation of the Developed Numerical Model

The purpose of model calibration is to adjust an appropriate set of model parameters so that the model can simulate the field measured heads and flow rates as much accurately as possible. During the calibration process, the model parameters are adjusted within an allowable range of geologically reasonable values.

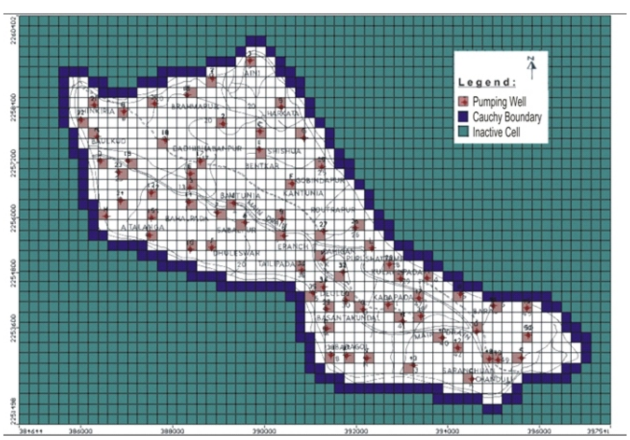

Fig. 2. Design of finite difference grid of the study area with boundary conditions and location of pumping nodes

In the present study, following standard modelling protocol, the developed groundwater-flow simulation model was first calibrated for the steady-state condition and then for the transient condition. The solution of the steady-state calibration was used as an initial condition for the transient calibration. Transient calibration was performed using weekly groundwater level data of 19 selected sites for the period 01 February 2004 to 04 June 2006, following the standard procedures (Anderson and Woessner, 1992; Zheng and Bennett, 2002; Bear and Cheng, 2010). A combination of trial and error technique and automated calibration code PEST was used to calibrate the developed flow model by adjusting the hydraulic conductivity, specific storage and recharge within reasonable ranges. The hydraulic conductivity and specific storage were calibrated within 50 to 200% of the originally estimated values, whereas the recharge was calibrated within 90 to 110% of the initially computed value. In order to take care of the spatial variation of recharge, the recharge zoning was done similar to the zoning of hydraulic conductivity parameter, and the zone-wise calibration of recharge was carried out. The calibration results were evaluated relative to the observed values at the 19 sites both quantitatively and qualitatively. After calibration of the model, validation was performed using the observed groundwater level data from June 2006 to May 2007. The calibrated hydraulic conductivity and storage coefficient values were used during validation of the model whereas other input parameters like pumping, river stage, recharge and observation head of the corresponding validation period were used.

Criteria Used for Model Evaluation

Six statistical criteria (or statistical indicators) were used to evaluate the performance of the calibration and validation of the numerical model. They are mean absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE, correlation coefficient (r) and Nash-Sutcliffe efficiency (NSE). These statistical indicators are expressed by the following equations:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|h_{si} - h_{oi}\right| \quad \text{...(2)}$$

$$SEE = \sqrt{\frac{\frac{1}{N-1}\sum_{i=1}^{N}\left[\left(h_{si} - h_{oi}\right) - \frac{1}{N}\sum_{i=1}^{N}\left(h_{si} - h_{oi}\right)\right]^2}{N}} \quad \text{...(3)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(h_{si} - h_{oi}\right)^2}{N}} \quad ...(4)$$

$$Normalized\ RMSE = \frac{RMSE}{\left(h_o\right)_{\max} - \left(h_o\right)_{\min}} \quad ...(5)$$

$$r = \frac{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)\left(h_{si} - \overline{h_s}\right)}{\sqrt{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)^2 \sum_{i=1}^{N}\left(h_{si} - \overline{h_s}\right)^2}} \quad ...(6)$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(h_{oi} - h_{si}\right)^2}{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)^2} \quad ...(7)$$

Where, h_{oi} = observed groundwater level of the i^{th} data [L], h_{si} = simulated/predicted groundwater level of the i^{th} data, $\overline{h}_o$ = mean of observed groundwater levels [L], $\overline{h}_s$ = mean of simulated groundwater levels [L], $(h_o)_{max}$ = maximum observed groundwater level [L], $(h_o)_{min}$ = minimum observed groundwater level [L], and N = number of observations. The best-fit between observed and simulated groundwater levels under ideal conditions would yield MAE = 0, SEE = 0, RMSE = 0, normalized RMSE = 0, r = 1 and NSE = 1.

Sensitivity Analysis

Sensitivity analysis is another component of model evaluation, which addresses uncertainty in modeling. Due to the uncertainties in estimating the aquifer parameters, stresses and boundary conditions, a sensitivity analysis is an essential step in modeling studies (Anderson and Woessner, 1992). This is particularly important when many parameters are to be optimized 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. In the present study, the sensitivity analyses on the calibrated and validated model were performed considering hydraulic conductivity, specific storage, recharge, river-bed conductivity and river stage. A 50% increase and decrease of these parameters/inputs were considered, whereas 0.5 m increase and decrease in the river stage were considered to assess the sensitivity of the model.

Simulation of Salient Groundwater Scenarios

The calibrated and validated groundwater model can be used for a variety of water resources planning and management studies (Anderson and Woessner, 1992; Rushton, 2003; Zheng and Bennett, 2010). The developed model was used to perform predictive simulations to examine the response of the aquifer to different pumping levels and to simulate ground water levels in the long run under existing pumping conditions. The following two major management scenarios were simulated and predicted using the calibrated groundwater flow simulation model.

(a) Scenario 1: ***Response of the aquifer to various pumping levels*** **-** The groundwater level in the study area was simulated for five pumping levels, *i.e.* 50%, 75%, 100%, 125% and 150% of the present pumping rates. The response of groundwater level to these pumping scenarios was evaluated using the calibrated groundwater flow simulation model.

(b) Scenario 2: ***Groundwater scenario during coming 15 years under existing pumping conditions*** **-** Under this scenario, keeping all the existing conditions constant, the effect of continuation of present pumping on groundwater level after 15 years was examined. The changes in groundwater level over the years were compared.

3. RESULTS AND DISCUSSION

Calibrated Model Parameters

The statistical indicators and well hydrographs

Table: 1
Calibrated values of the parameters

Site	Kh (m day^{-1})	S_s	Monthly average recharge (mm yr^{-1})	
			Wet season	Dry season
A	20	4.3×10^{-6}	639.67	174.77
B	20	4.3×10^{-6}	639.67	174.77
C	27	5.3×10^{-6}	639.67	174.77
D	32	4.3×10^{-6}	639.67	174.77
E	23	2.3×10^{-5}	546.63	149.35
F	27	5.3×10^{-6}	639.67	174.77
G	27	5.3×10^{-6}	639.67	174.77
H	32	6.5×10^{-6}	639.67	174.77
I	23	2.3×10^{-5}	546.63	149.35
J	41	6.5×10^{-6}	523.37	142.99
K	44	1.16×10^{-5}	552.44	150.94
L	44	1.16×10^{-5}	552.44	150.94
M	52	2.75×10^{-5}	523.37	142.99
N	52	2.75×10^{-5}	523.37	142.99
O	52	2.75×10^{-5}	523.37	142.99
P	45	2.75×10^{-5}	639.67	174.77
Q	45	8.4×10^{-6}	639.67	174.77
R	47	8.4×10^{-6}	639.67	174.77
S	47	8.4×10^{-6}	639.67	174.77
Mean	35	1.24×10^{-5}	593.80	162.24

comparing observed and simulated groundwater levels showed a reasonably good calibration of the numerical model. The detailed results of model calibration are presented in Mohanty *et al.* (2013). Table 1 shows the calibrated values of hydraulic conductivity and specific storage of the aquifer alongwith the average monthly recharge during wet season (June to October) and dry season (November to May). The calibrated values of hydraulic conductivity vary from a minimum of 20 m day^{-1} (sites A and B) to a maximum of 52 m day^{-1} (sites M, N and O), whereas the calibrated values of aquifer specific storage remains more or less the same (varying from 1.43×10^{-4} to 9.9×10^{-4}) as the measured values. On the other hand, the calibrated values of average monthly recharge in the wet season vary from about 523 mm yr^{-1} to 640 mm yr^{-1}, whereas they vary from 143 mm yr^{-1} to 175 mm yr^{-1} in the dry season.

Groundwater Scenario in Dry and Wet Seasons

Fig. 3 shows a simulated groundwater-level contour map of the study area for the representative dry season (1st May 2004). Similarly, Fig. 4 shows simulated groundwater-level contour map of the study area for the representative wet season (27th August 2004). It is evident from Fig. 3 that the groundwater level varies from an elevation of 15.5 m (msl) in the upstream side to 11.0 m (msl) in the downstream side during dry season. However, during wet season, the groundwater level varies from an elevation of 18.5 m (msl) in the upstream side to 15.5 m (msl) in the downstream side. Thus, there is a spatial variation of 4.5 m in the groundwater level in the dry season, while it is 3.0 m in the wet season. As far as temporal variation of groundwater levels in the study area is concerned, a seasonal variation of 3.0 m is discernable in the upstream side of the basin and of 4.5 m in the downstream side.

The velocity vectors of the groundwater level during dry and wet seasons show flow of ground water from the river towards the aquifer from both sides of the basin, which converges near the main drain of the study area. The overall flow pattern is from north-west to south-east direction. A close perusal of the groundwater level-contour map of the dry season (Fig. 3) show that the velocity of groundwater is higher in the middle of the basin, which is represented by larger size of arrows and closer spacing between groundwater-level contour lines. In the downstream portion of the study area, there is lower velocity of groundwater which is represented by smaller size of arrows and wider spacing between groundwater-level contour lines. The velocity of groundwater from the Kathajodi river is somewhat higher than that from the Surua river as indicated by closer groundwater-level contour lines and comparatively large velocity vectors near the Kathajodi river side of the basin.

The groundwater-level contour map of the wet season (Fig. 4) reveals that in this season also the velocity of groundwater is lower towards the downstream side of the basin. There is mostly upward flow of water (represented by blue-color velocity vectors) from the aquifer during wet season as compared to mostly downward flow of water (represented by maroon-color velocity vectors) to the aquifer during dry season. This finding is attributed to the fact that due to more pumping and less recharge during dry season, there is a gradual decrease in

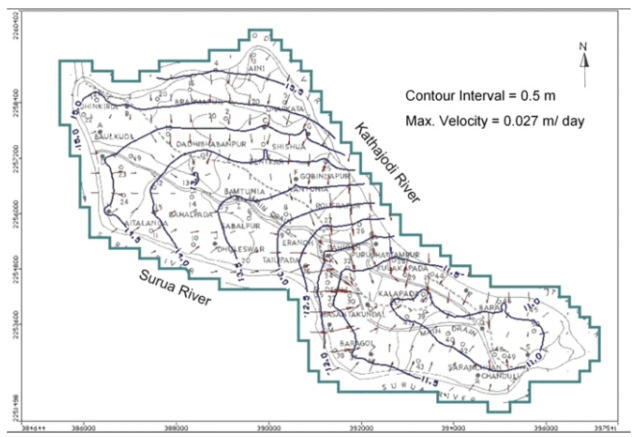

Fig. 3. Groundwater level contour map of a representative dry season (1st May 2004) with groundwater flow vectors

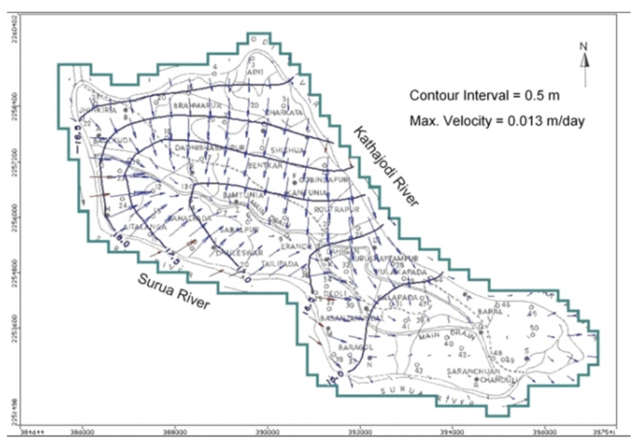

Fig. 4. Groundwater level contour map of a representative wet season (27th August 2004) with groundwater flow vectors

groundwater levels and hence downward groundwater flow in study area. In contrast, due to recharge from rainfall and seepage from the rivers during wet season, there is a gradual increase in groundwater levels and hence upward groundwater flow prevails in the study area.

Results of Model Validation

Table 2 presents mean absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE, correlation coefficient (r) and Nash-Sutcliffe efficiency (NSE) values at 18 sites during validation of the developed groundwater flow model. The MAE values vary from a minimum of 0.297 m at Site Q to a maximum of 0.709 m at Site M, whereas the SEE values range from a minimum of 0.051 m at Site G to a maximum of 0.112 m at Site E. The RMSE values vary from a minimum of 0.38 m at Site Q to a maximum of 0.827 m at Site E, whereas the normalized RMSE values range from a minimum of 6.27% at Site Q to a maximum of 19.51% at Site C. The correlation coefficient values range from a minimum of 0.922 at Site H to a maximum of 0.982 at Site Q, whereas the NSE values range from a minimum of 0.55 at Site C to a maximum of 0.95 at Site Q. Thus, there has been relatively superior simulation of groundwater levels at sites D, K, Q and S as the values of MAE and RMSE values are on a lower side, and those of r and NSE values are on a higher side. However, there has been relatively inferior simulation of groundwater levels at sites B, C, E and M as suggested by relatively high values of MAE and RMSE, and relatively low values of r and NSE. Overall, there is good simulation of groundwater levels because the MAE, SEE, RMSE, and normalized RMSE values for almost all the sites are reasonably low and within acceptable limits. Also, the values of correlation coefficient and NSE are reasonably high at most of the sites.

Table: 2
Model performance statistics during validation period

Site	Validation period (June 2006 to May 2007)					
	MAE (m)	SEE (m)	RMSE (m)	Normalized RMSE (%)	r	NSE
A	0.536	0.075	0.717	13.94	0.931	0.763
B	0.568	0.072	0.677	15.54	0.924	0.718
C	0.657	0.107	0.775	19.51	0.944	0.550
D	0.343	0.060	0.493	9.31	0.955	0.884
E	0.658	0.112	0.827	16.25	0.968	0.670
F	0.613	0.102	0.737	13.40	0.935	0.706
G	0.436	0.051	0.542	10.37	0.967	0.855
H	0.511	0.090	0.657	12.41	0.922	0.826
I	0.529	0.082	0.697	13.75	0.981	0.775
J	0.417	0.081	0.600	12.15	0.922	0.841
K	0.400	0.058	0.505	8.36	0.973	0.912
L	0.379	0.061	0.522	7.82	0.964	0.900
M	0.709	0.104	0.812	11.39	0.968	0.843
O	0.424	0.059	0.563	8.82	0.974	0.885
P	0.520	0.052	0.631	10.19	0.976	0.853
Q	0.297	0.053	0.380	6.27	0.982	0.945
R	0.396	0.066	0.552	8.88	0.972	0.907
S	0.416	0.055	0.486	7.71	0.977	0.922
Mean	0.489	0.020	0.632	6.53	0.958	0.914

Results of Sensitivity Analysis

It was observed that the model is more sensitive to the changes in the hydraulic conductivity and recharge and is least sensitive to changes in the specific storage. The increases in hydraulic conductivity resulted in decrease in groundwater levels in the wet season and increase in groundwater levels in the dry season. The decreases in hydraulic conductivity resulted in increase in groundwater levels in the wet season and decrease in groundwater levels in the dry season. However, the deviation of groundwater levels due to changes in specific storage was very negligible at all the sites for all the time periods. This indicates the insensitiveness of the model to changes in the aquifer specific storage. This finding suggests that the uncertainty associated with hydraulic conductivity will significantly affect the model's ability to make reliable predictions. On the other hand, the uncertainty in specific storage parameter will have little impact on the model's predictive abilities. It was also observed that the model results are more sensitive to changes in the river stage, whereas the river-bed conductivity has a very less effect on the model results. This indicates the importance of river in maintaining high ground water levels in alluvial aquifer systems. Therefore, the river stage should be measured with high precision compared to the river-bed conductivity so as to ensure reliable model predictions.

Simulated Groundwater Scenarios for the Study Area

Scenario 1: ***Aquifer response to different pumping levels-*** It was observed that the increase or decrease in pumping rates upto 50% did not result in any significant changes in the groundwater levels during the standard weeks 30-50, which mostly coincides with the wet season. This can be attributed to the fact that less pumping is done in the wet season and also significant recharge from rainfall or river occurs during this period. On the contrary, the changes in the groundwater levels were more pronounced in the dry season where the increase or decrease in pumping rate resulted in significant decrease or increase in groundwater levels.

Scenario 2: ***Future groundwater scenario-*** The simulated groundwater levels at five sites distributed over the study area, *i.e.* Baulakuda (Site A), Gobindpur (Site G), Dhuleswar (Site J), Kalapada (Site O) and Chanduli (Site S) for a 15 period (2007-2022) is shown in Fig. 5. The figure shows that with the continuation of existing management practices, there is no significant change in groundwater level even after 15 years of pumping at all the sites. Out of the five sites, the groundwater levels at sites O and S are observed relatively lower than the other sites throughout the simulation period. The Kathajodi-Surua Inter-basin is a complete river island surrounded by two rivers and due to this, the effect of the boundary conditions (rivers) on groundwater levels has been found very significant. The water that is pumped from the aquifer is being replenished by the river, and hence there is no significant change in groundwater levels even in the long run. Thus, if the existing conditions continue, there is no threat to the groundwater lowering in the study area for coming 15 years.

4. CONCLUSIONS

In this paper, numerical analysis of a deltaic aquifer system using finite difference-based modeling system, 'Visual MODFLOW' is presented. Numerical analysis includes the sensitivity analysis of the developed groundwater-flow simulation model, simulation of salient groundwater management scenarios and the analysis of groundwater condition during wet and dry seasons. The results of sensitivity analysis indicated that the groundwater level is more sensitive to the river stage followed by recharge and hydraulic conductivity, but it is least sensitive to changes in the specific storage of the aquifer system. Keeping all the existing conditions constant, the effect of the continuation of present level of pumping on groundwater in next 15 years (2007-2022) was examined. The simulation results revealed that there will be no significant change in groundwater levels over the study area up to the year 2022 under existing conditions. The study area being a river island surrounded by the rivers, the decrease in aquifer storage is replenished by the seepage from the rivers. Thus, under the existing hydrologic and hydrogeologic conditions, there is no threat of groundwater decline in the near future.

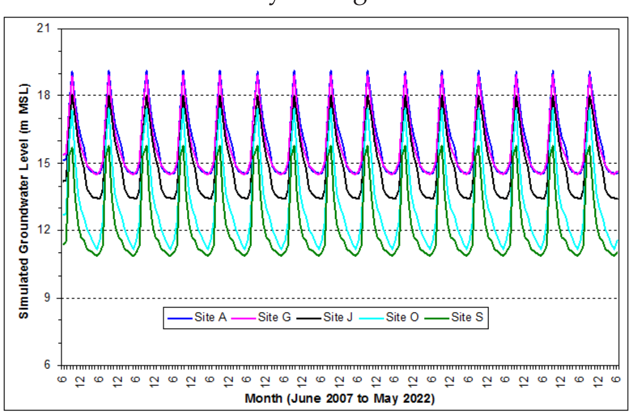

Fig. 5. Simulated groundwater levels for the fifteen year period

The methodology demonstrated in this study can be useful in developing groundwater-flow simulation models for other regions of India as well as for other parts of the world. Properly developed groundwater-flow models in conjunction with optimization models can help formulate efficient management strategies for sustainable water resources management under changing climatic and socio-economic conditions.

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