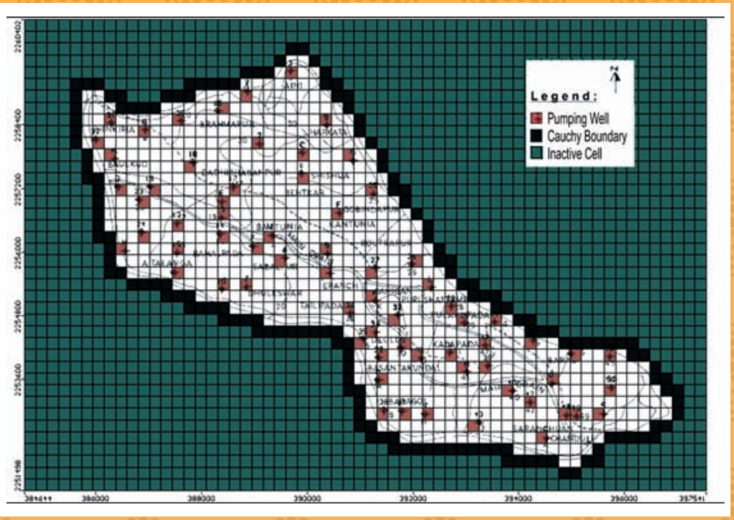
भाकृअनुप
ICAR

Research
Bulletin
72

GROUNDWATER MODELING FOR SUSTAINABLE AQUIFER MANAGEMENT IN A RIVER ISLAND OF EASTERN INDIA



Sheelabhadra Mohanty
Madan K. Jha
Ashwani Kumar
Ramesh C. Srivastava

जल प्रबंधन निदेशालय
D. W. M
DWM

Directorate of Water Management
(Indian Council of Agricultural Research)
Bhubaneswar - 751023, Odisha, India
2014

Research Bulletin No. : 72

भाकृअनुप
ICAR

Groundwater Modeling for Sustainable Aquifer Management in a River Island of Eastern India

Dr. Sheelabhadra Mohanty

Dr. Madan K. Jha

Dr. Ashwani Kumar

Dr. Ramesh C. Srivastava

जल प्रबंधन निदेशालय
D. W. M

Directorate of Water Management
(Indian Council of Agricultural Research)
Bhubaneswar - 751023, Odisha, India

2014

Correct citation:

Mohanty, Sheelabhadra; Jha, Madan K.; Kumar Ashwani; Srivastava, Ramesh C., 2014. Groundwater Modeling for Sustainable Aquifer Management in a River Island of Eastern India. Bulletin No.-72. Directorate of Water Management, Indian Council of Agricultural Research, Chandrasekharpur, Bhubaneswar, India,37p.

© 2014, Directorate of Water Management (ICAR).

Published by:

Director,
Directorate of Water Management
(Indian Council of Agricultural Research)
Chandrasekharpur, Bhubaneswar, Odisha, 751023, India.
Phone: 91-674-2300060;EPBAX: 91-674-2300010, 2300016
Fax: 91-674-2301651;

Printed at:

S J Technotrade (P) Ltd.
Subarnarekha Chambers,
Plot No : A-9 & 10, Unit – IV,
Bhouma Nagar, Bhubaneswar – 751001
E-Mail : info.mailtechnotrade@gmail.com
Cell: 9132573795
Email : info.technotrade@gmail.com

PREFACE

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Because of its several inherent qualities as well as the relative ease and flexibility with which it can be tapped, it has become most reliable and very important source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries. It is estimated that groundwater provides about 50% of the current global domestic water supply, 40% of the industrial supply, and 20% of water use in irrigated agriculture.

However, the aquifer depletion due to over-exploitation and the growing pollution of groundwater are threatening our sustainable water supply and ecosystems worldwide. Hence the key concern is how to maintain a long term sustainable yield from the aquifer in the face of impending climate change and socio-economic factors. The groundwater simulation models have emerged as the tool of choice among water resources researchers and planners for addressing questions about the impacts of groundwater development. These models are useful in simulating groundwater flow scenarios under different management options, thereby taking corrective measures for the efficient utilization of water resources by conjunctive use of surface water and groundwater.

In the current study, a groundwater flow simulation model has been developed for simulating groundwater scenarios in Kathajodi-Surua Inter-basin within Mahanadi Deltaic system of Odisha. The Visual MODFLOW software has been used which is a well recognized standard groundwater model used by various regulatory agencies, universities, consultants and industry both in developed and developing countries. Calibration and validation of the model has been done by comparing the simulated and observed groundwater levels. The developed model will be helpful for developing management strategies for efficient utilization of water and land resources in the river basin. The present study is first of its kind in the study area. The methodology demonstrated in this study being generic in nature, will also be useful for other regions of the country.

Authors

CONTENTS

1. Introduction

Groundwater is a very important and invaluable natural resource. It is renewable but finite resource, which is generally characterized by stable temperature and chemical composition. Its unique qualities that it is generally free from pathogens, easily accessible and free from suspended particles has made it the most important and preferred source of water for agricultural and domestic uses. However, overexploitation of groundwater can result in adverse effects on the local and regional ecosystems. A growing number of regions are facing increasing water stresses owing to burgeoning water demands, profligate use, and escalating pollution worldwide (Rodda, 1992; Biswas, 1993; Falkenmark and Lundqvist, 1997). Hence, the key 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 impending climate effects and socio-economic change

In India, the demand for water has already increased a multiple times over the years due to increasing population, growing urbanization, agriculture expansion, rapid industrialization and economic development and the water demand has an increasing trend in all the sectors (Kumar et al., 2005; Mall et al., 2006). It is projected that most irrigated areas in India would require more water around 2025 and global net irrigation requirements would increase relative to the situation without climate change by 3.5–5% by 2025, and 6–8% by 2075 (Doll and Siebert, 2001). Already there are several areas of the country that face water scarcity due to intensive groundwater exploitation (CGWB, 2011). The experiences in the field of water management in India have shown that unbalanced use of water resources have either lowered groundwater level or caused waterlogging and salinity in different parts of the country (Jha et al., 2001). Particularly, in the canal-dominated regions of North India, there has been increase in groundwater levels due to seepage from the canals. Excessive pumping on the other hand has led to alarming decrease in groundwater levels in several parts of the country. This in turn has increased the cost of pumping, caused seawater intrusion in the coastal areas and has raised questions about the future availability of groundwater. Therefore, efficient and judicious utilization of surface and groundwater resources is very much essential for sustainable water resources management.

The groundwater simulation models have emerged as the tool of choice among water resources researchers and planners for addressing questions about the impacts of groundwater development (Anderson and Woessner, 1992; Rushton, 2003). These models are useful in simulating groundwater flow scenarios under different management options, thereby taking corrective measures for the efficient utilization of water resources by conjunctive use of surface water and groundwater. The simulation approach attempts to replicate real world complexity by integrating components of the physical hydrogeologic system, climatic effects, and anthropogenic stresses, thereby providing insight not only into changes within the aquifer but also on their interaction with overlying surface water systems (Zume and Tarhule, 2008). Recently, groundwater simulation models are being widely used in different parts of the world. However, basin-wide groundwater modeling studies in India are in its infancy due to the lack of adequate field data, financial resources, infrastructure and proper technical knowledge. Very limited studies on groundwater modeling in river basins have been conducted in India (Ahmed and Umar, 2009; Raul et al., 2011; Elango et al., 2012).

Therefore, a study on development of groundwater flow simulation model in a river basin by using a physically based model Visual MODFLOW has been done in order to understand the dynamics of groundwater flow and develop strategy for optimal groundwater utilization. For this, a study area Kathajodi-Surua Inter-basin has been selected within the Mahanadi deltaic system of Orissa. The study area is a river island, which is surrounded by the Kathajodi River and its branch Surua on all sides. The present study is first of its kind in the study area.

2. Study Area

The study area 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 locally called as 'Bayalish Mouza' and is located between 85^{o} 54' 21” to 86^{o} 00' 41” E longitude and 20^{o} 21' 48” to 20^{o} 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 about 80% occurs during June to October months. The normal mean monthly maximum and minimum temperatures of the region are 38.8^{o} C and 15.5^{o} C in May and December, respectively. The mean monthly maximum and minimum evapotranspiration rates are 202.9 mm and 80.7 mm in May and December, respectively.

Fig. 1: Location Map of the Kathajodi-Surua Inter-Basin

Agriculture is the major occupation of the inhabitants. Total cultivated area in the study area is 2445 ha, of which 1365 ha is irrigated land. The area under low land is 408 ha, medium land 1081 ha and high land is 956 ha. Paddy is the major crop in the monsoon season, whereas crops like vegetables, potato, groundnut, greengram, blackgram and horsegram are grown in the post-monsoon season. Owing to the lack of irrigation infrastructure for surface water, all the irrigated lands are irrigated by groundwater. At present there are 69 functioning government tubewells in the study area, which are the major sources of groundwater withdrawal. These tubewells were earlier constructed and managed by Orissa Lift Irrigation Corporation (OLIC), Cuttack, Orissa, but now they have been handed over to the water users' associations (WUAs). Although there is no water shortage during the monsoon season, in the summer season, the farm ponds dry up and the groundwater supply is not sufficient to meet the entire water demand for irrigation.

During the monsoon season, a different kind problem, i.e. waterlogging is encountered in the study area. Embankments have been provided on the banks of the rivers to prevent the entry of river water into the inhabited area during flood events. Therefore, entire rainwater of the region is drained through the main drain and discharged at a single outlet into the river. A sluice gate is provided at the outlet of the area to prevent entry of river water during flood events. During this time, surface waterlogging problem is often encountered in the downstream side of the study area.

2.1 Groundwater monitoring

Since no groundwater data were available in the study area, a groundwater monitoring program was initiated in February 2004. For the monitoring of groundwater levels, nineteen tubewells were selected spread over the study area. The locations of the nineteen monitoring wells are shown as red circles (A to S) in Fig. 2. The other tubewells are shown as blue circles (1 to 50). Groundwater levels were monitored in the 19 tubewells on a weekly basis from February 2004 to October 2007. The geographic locations of the tubewells in the study area were found with the help of a global positioning system (GPS) and the elevations of the tubewell sites were determined by leveling survey.

3. Development of Groundwater Flow Simulation Model

A groundwater-flow simulation model was developed using Visual MODFLOW (VM) version 4.1 software. Major steps involved in the design and development of the model are development of a conceptual model of the study area, identifying governing equation, selection of grid design, assignment of initial and boundary conditions and estimation of model parameters.

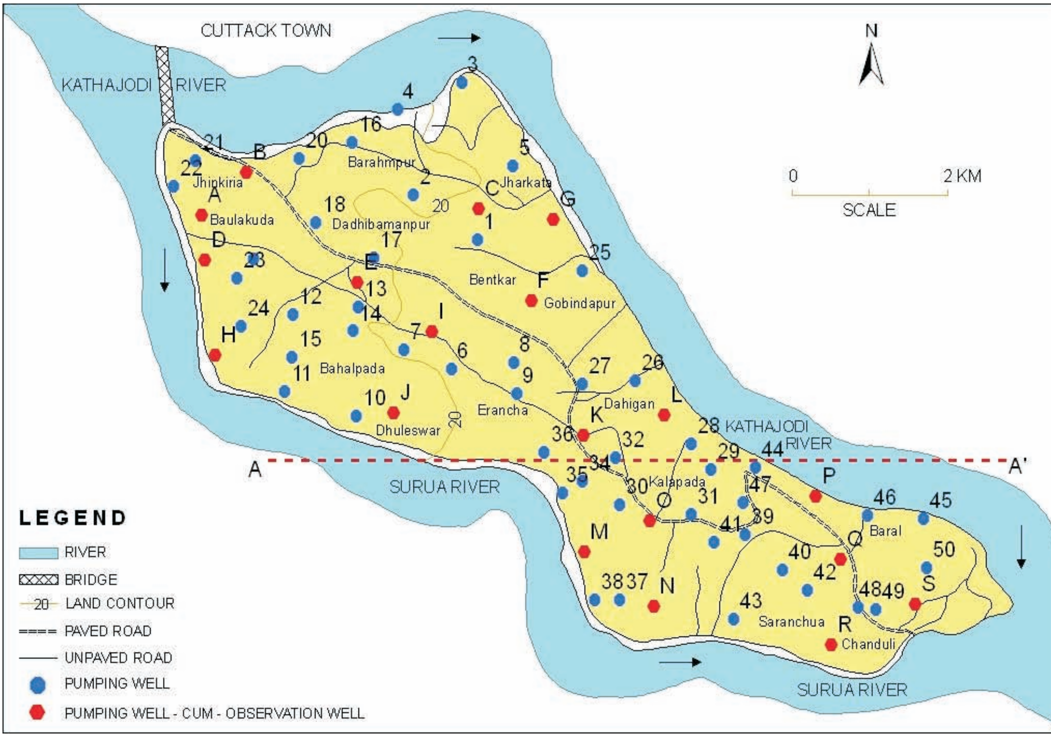


Fig. 2: Location of Observation and Pumping Wells in the Study Area

3.1 Development of conceptual model

A key step in groundwater modeling procedure is to develop a conceptual model of 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 more 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.

A conceptual model of the aquifer system prevalent in the study area was developed based on the hydrologic and hydrogeologic analysis and field investigations. The lithologic analysis indicated that a confined aquifer exists in the river basin which was the focus of the study. 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 lower confining layer is present at a depth of 65 to 87 m and consists of clay. The upper confining layer mostly consists of clay and sandy clay, whereas the aquifer material is comprised of medium sand to coarse sand. There are patches of medium sand and coarse sand within the clay bed of upper confining layer which makes it leaky confining layer, and hence the aquifer was characterized as a leaky confined aquifer. There are some scattered clay lenses present in the aquifer layer. These clay lenses were ignored while developing the conceptual model of the study area.

The eastern boundary is bounded by the Kathajodi River and the western boundary is bounded by the Surua River (Fig. 2). Therefore, these boundaries were simulated as Cauchy (head-dependant flux) boundary conditions. The recharge from rainfall and other sources act as source to the model whereas, the groundwater extractions through the tubewells act as sink from the model. The conceptual model of the study area at Section A-A' (Fig. 2) is shown in Fig. 3, which provides a basis for the design and development of the numerical model of the study area using Visual MODFLOW software.

3.2 Governing equation

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

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

Where, Kx, Ky, and Kz = 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}]; Ss = specific storage of the aquifer, [L^{-1}]; and t = time, [T].

The above governing equation of groundwater flow was solved by finite difference method using MODFLOW software.

3.3 Discretization of the basin and model design

The study area was discretized into 40 rows and 60 columns using the Grid module of Visual MODFLOW software (Fig. 4). This resulted in 2400 cells, each having dimension of approximately 222 m X 215 m. The cells lying outside the study area were assigned as inactive cells.

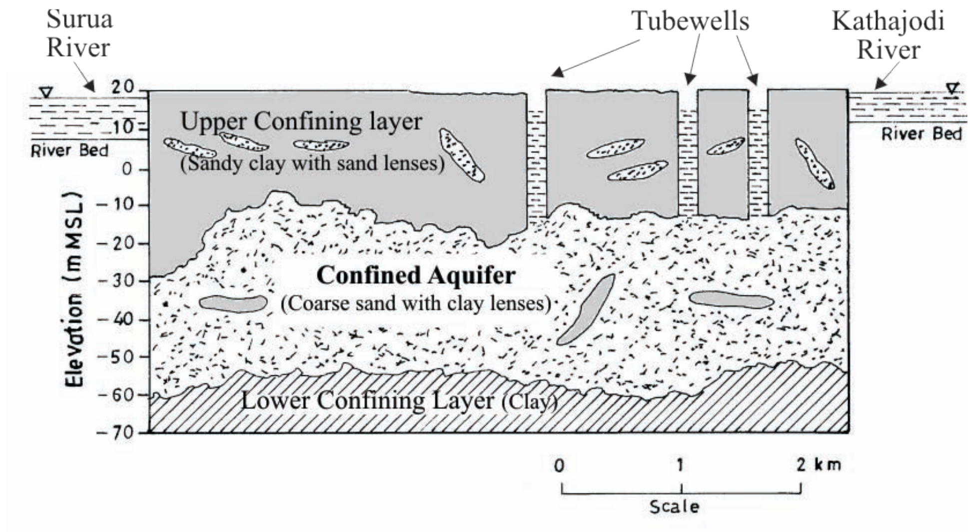


Fig. 3 (a): Representative Lithiologic Section of the Kathajodi-Surua Inter-basin

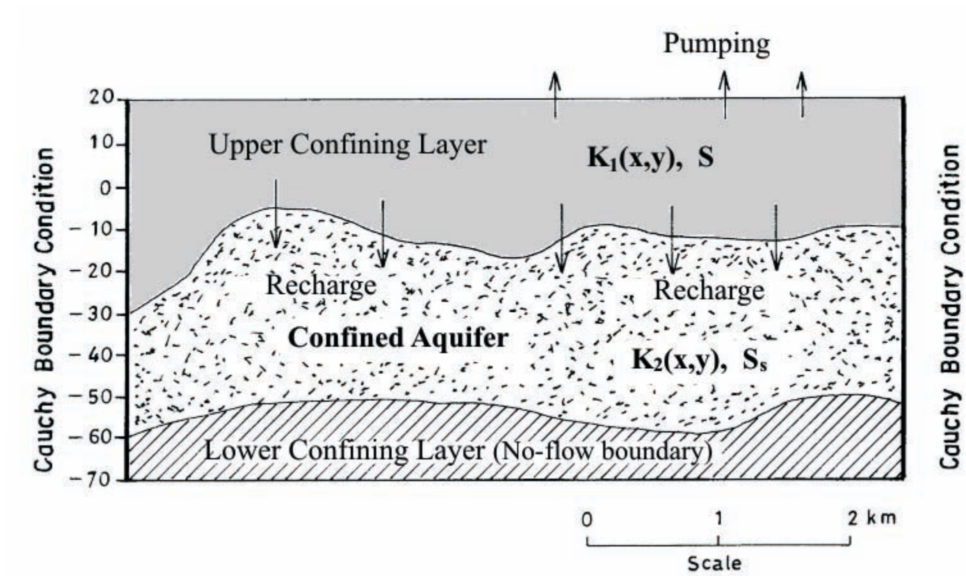


Fig. 3 (b): Conceptual Model of the Kathajodi-Surua Inter-basin

The hydrogeologic setting of the study area as conceptualized earlier was divided into two model layers with the lower one representing the confined aquifer. The thickness of the two layers at different points was assigned considering the hydrogeologic framework of the study area. The thickness of the upper layer varied from 15 to 50 m, whereas the thickness of the lower layer (i.e., confined aquifer) varied from 20 to 55 m. The data on surface elevation, bottom elevation of the top layer and bottom elevation of the aquifer layer at available 19 sites were imported to the MODFLOW software from the database prepared using MS-Excel files. Similarly, the location of pumping wells, observation wells and weekly groundwater levels of the model period were also imported from the MS-Excel databases. Fig. 5(a) shows the 3-D cross section of the aquifer underlying the study area along with the cells and pumping wells in the Visual MODFLOW model. The cross sections along the section are depicted by using the 3D-Explorer module of Visual MODFLOW. Similarly, Fig. 5(b) shows the 3-D cross section of the aquifer along with the cells and observation wells.

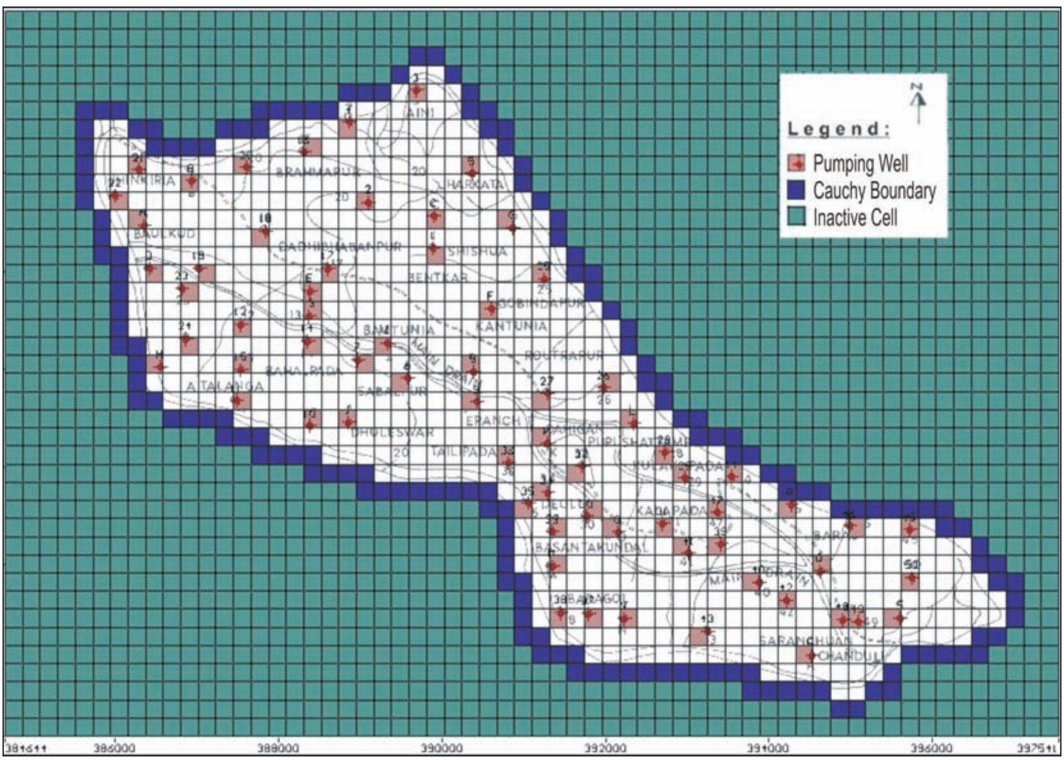


Fig. 4: Design of Finite Difference Grid of the Study Area with Boundary Conditions and Location of Pumping Nodes

3.4 Assignment of boundary conditions

The Kathajodi and Surua rivers completely surround the basin from the east and west directions, respectively making this study area a complete river island. Therefore, the boundaries of the groundwater basin were modeled as head-dependent flux or Cauchy boundary condition. The river heads were monitored periodically and were assigned as varying head boundary conditions using the 'River Package' of Visual MODFLOW software. The base of the aquifer was modeled as a no-flow boundary, because it consists of dense clay. The river boundary around the study area as modeled in Visual MODFLOW software has been depicted in Fig. 4.

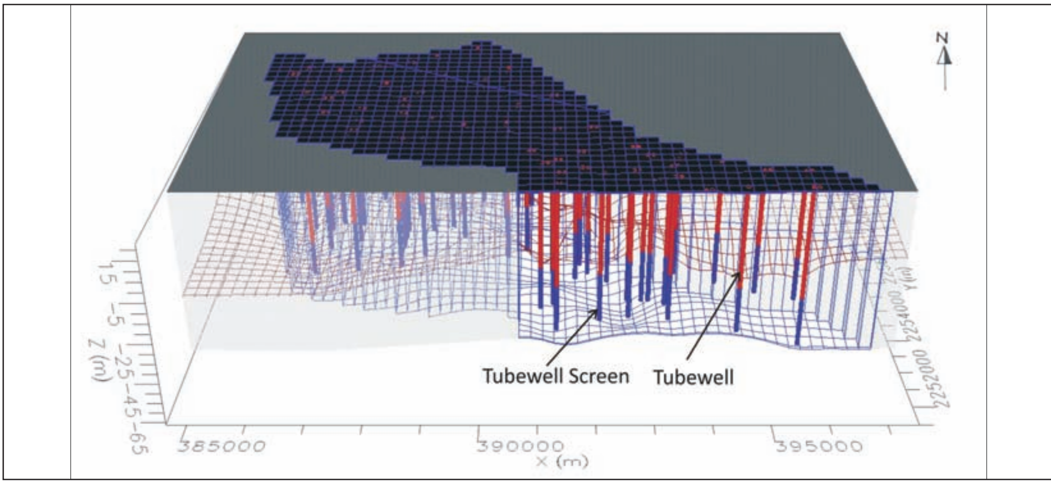


Fig. 5(a): Cross-section of the Modeled Study Area Showing the Pumping Wells

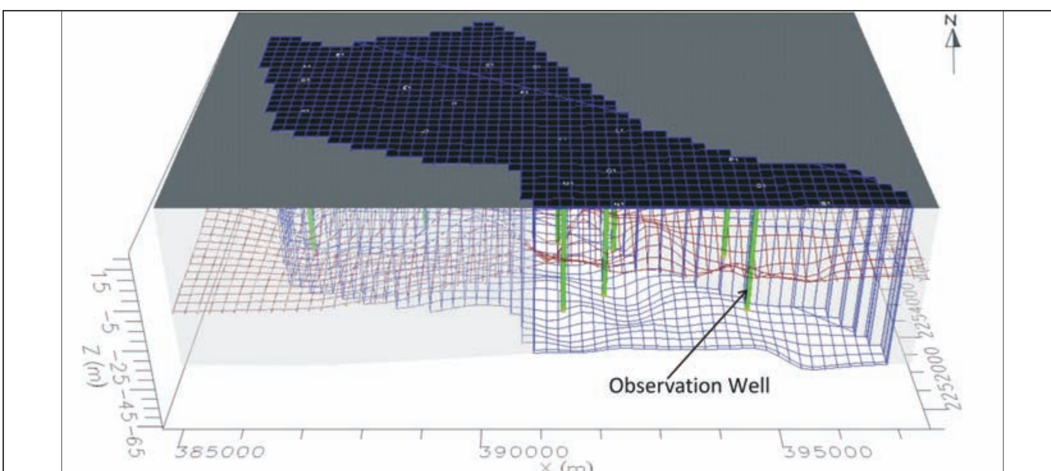


Fig. 5(b): Cross-section of the Modeled Study Area Showing the Observation Wells

Core samples were taken from 10 locations along the river bed and the hydraulic conductivity of the river bed was determined in the laboratory by constant head permeameter method. The water flux between the rivers and the aquifer was simulated by dividing the rivers into 10 reaches. The input parameters such as river stage at different time steps, river-bed elevation, river-bed conductivity, river-bed thickness, and river width at the upstream and the downstream site for all the river reaches were assigned. MODFLOW linearly interpolates these values between both the ends of a river reach.

3.5 Initial conditions

Initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation and thus are boundary conditions in time. It is a standard practice to select as the initial condition a steady state head solution generated by a calibrated model (Anderson and Woessner, 1992). In this study, steady state head solution of 1st February 2004 groundwater level was used as the initial condition for the calibration period and steady state head solution of 4th June 2006 groundwater level was used as the initial condition for the validation period. Based on the groundwater data availability, week was chosen as the time step within which all hydrological stresses were assumed constant.

3.6 Estimation of model parameters

The Visual MODFLOW software require assignment of model parameters like aquifer properties, sources and sinks, groundwater level distribution and spatial and temporal distribution of recharge, evapotranspiration etc. The model input included hydrogeological parameters such as hydraulic conductivity (K) and specific storage (Ss), groundwater abstraction, distribution of groundwater level heads and groundwater recharge. As the aquifer in the present study is confined/semi-confined in nature, the evapotranspiration was not considered as an input to the model. The estimation of the model parameters is described as follows.

(a) Aquifer parameters

The hydraulic conductivity (K) and specific storage (Ss) values of the confined aquifer under study were obtained from the pumping test data analysis at 9 sites. The distribution of aquifer hydraulic conductivity over the study area was grouped into 9 zones as shown in Fig. 6(a), whereas the distribution of specific storage was grouped into 7 zones [Fig. 6(b)]. For all the zones, a ratio of horizontal hydraulic conductivity (Kh) to vertical hydraulic conductivity (Kv) was assumed as 10 to account for aquifer anisotropy. It is a standard practice in groundwater modeling that whenever only horizontal hydraulic conductivity data is available, the Kh to Kv ratio is assumed as 10 for alluvial aquifer systems (WHI, 2005).

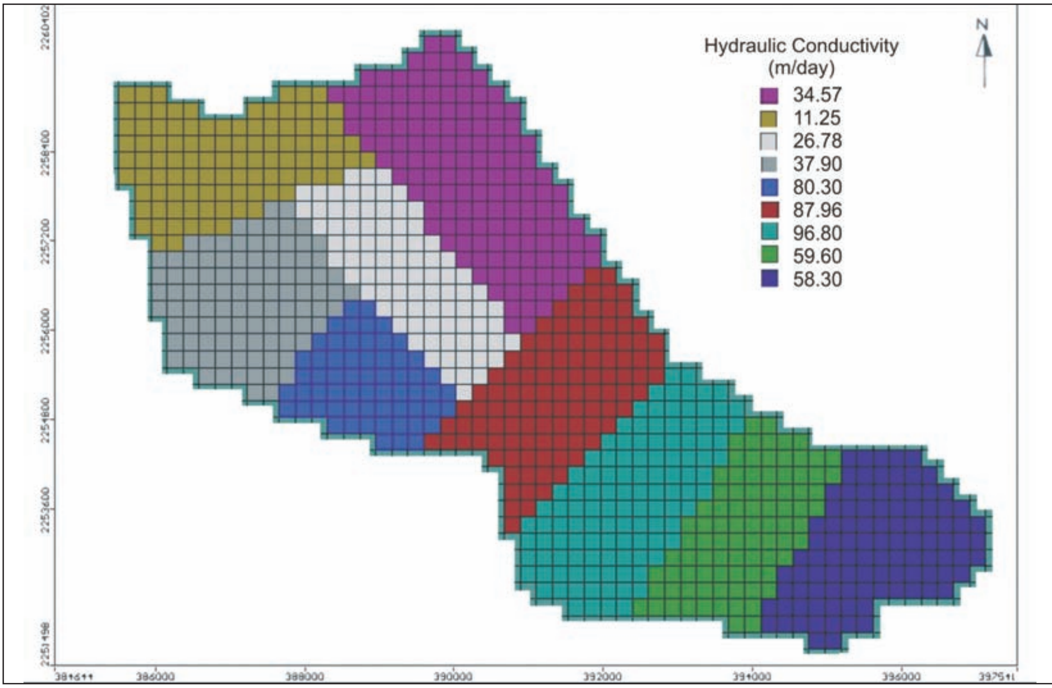


Fig. 6(a): Hydraulic Conductivity Zones in the Study Area

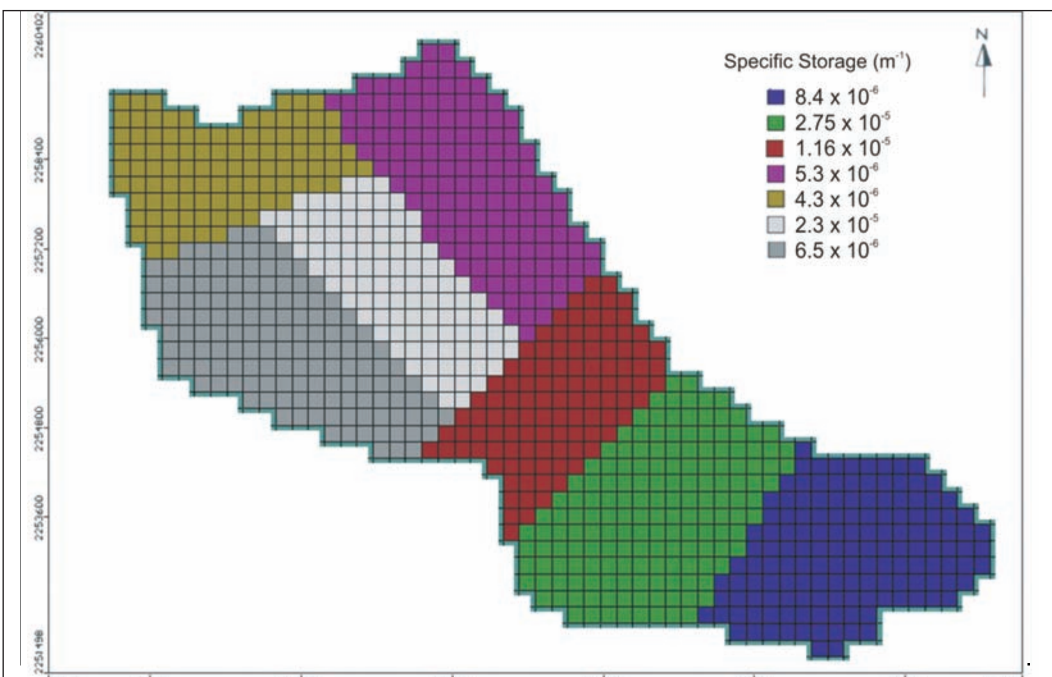


Fig. 6(b): Specific Storage Zones in the Study Area *(b) Groundwater abstractions*

The Well Package of MODFLOW software is designed to simulate inflows and outflows through recharge wells and pumping wells, respectively. As mentioned earlier, 69 tubewells are functioning in the study area. Since, the historical records of pumping from these tubewells were not available; a survey was made among the water users to find out the pumping schedule of different tubewells. The discharges of the tubewells were measured during field investigation and found to vary from 11.6 L/s to 26.2 L/s during the monsoon season. According to the officials of the Orissa Lift Irrigation Corporation (OLIC) and the local farmers, the average discharge of the tubewells reduces by about 5% during January to March and by about 10% during April to June. Thus, pumping rates averaged over the stress period along with the location of pumping wells were input to the groundwater flow model as sinks. The position and extent of the well screens of respective pumping wells were also assigned using the Well Package of the model.

(c) Groundwater recharge

The recharge package in MODFLOW is designed to simulate areal distributed recharge to the groundwater system. The monthly recharge estimated by an empirical method was input to the groundwater flow model. The recharge estimates might have a large uncertainty, and hence recharge was also used as a calibrating parameter.

4. Evaluation Criteria of the Simulation Model

In groundwater modelling studies, different criteria of evaluation like bias (also called residual mean or, mean error), mean absolute error (MAE) (also called absolute residual mean), root mean squared error (RMSE) and correlation coefficient (r) are generally used during calibration process. RMSE is one of the best measurements of error, if the errors are normally distributed (Anderson and Woessner, 1992). In this study, additional model evaluation statistics such as standard error of estimate (SEE), normalized RMSE, mean percent deviation (Dv), and Nash-Sutcliffe efficiency (NSE) have been used. In total, eight statistical criteria (or statistical indicators) were used in order to quantitatively evaluate the performance of the model during calibration and validation. They are bias, mean absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE, correlation coefficient (r), mean percent deviation (Dv) and Nash-Sutcliffe efficiency (NSE).

Bias

The bias is a measure of the average residual value defined by the equation:

$$Bias = \frac{1}{N}\sum_{i=1}^{N}\left(h_{si} - h_{oi}\right) \quad \ldots (2)$$

Where, h_{oi} = observed groundwater level of the ith data [L], h_{si} = simulated/predicted groundwater level of the ith data, and N = number of observations.

The positive values of bias indicate overall over-prediction by the model, while the negative values indicate overall under-prediction by the model. .

Mean absolute error (MAE)

The mean absolute error is similar to the bias except that it is a measure of the average absolute residual value defined by the equation:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|h_{si} - h_{oi}\right| \quad \ldots (3)$$

Mean absolute error measures the average magnitude of the residuals, and therefore provides a better indication of calibration than the bias.

Standard error of estimate (SEE)

The standard error of estimate is a measure of the variability of the residual around the expected residual value, and is expressed by the following equation:

$$SEE = \sqrt{\frac{\frac{1}{N-1}\sum_{i=1}^{N}\left[\left(h_{si} - h_{oi}\right) - \frac{1}{N}\sum_{i=1}^{N}\left(h_{si} - h_{oi}\right)\right]^2}{N}} \quad \ldots (4)$$

Root mean squared error (RMSE)

The root mean squared error is a widely accepted performance evaluation index, and is defined by the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(h_{si} - h_{oi}\right)^2}{N}} \quad \ldots (5)$$

Normalized RMSE

The normalized RMSE is the RMSE divided by the maximum difference in the observed head values. It accounts for the scale of the potential range of data values and is expressed by the following equation:

$$Normalized\ \ RMSE = \frac{RMSE}{(h_o)_{\max} - (h_o)_{\min}} \qquad \text{... (6)}$$

Where, $(h_o)_{max}$ = maximum observed groundwater level [L], and $(h_o)_{min}$ = minimum observed groundwater level [L].

Correlation coefficient (r)

The correlation coefficient is expressed by the following equation:

$$r = \frac{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)\left(h_{si} - \overline{h_s}\right)}{\sqrt{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)^2 \sum_{i=1}^{N}\left(h_{si} - \overline{h_s}\right)^2}} \qquad \text{... (7)}$$

Where, $\overline{h_o}$ = mean of observed groundwater levels [L],

Correlation coefficient determines whether two ranges of data move together, i.e., whether large values of one data set are associated with large values of the other data set, whether small values of one data set are associated with large values of the other data set, or whether values in both data sets are unrelated.

Mean percent deviation (Dv)

The mean percent deviation is a measure of the average deviation of the calculated data set from the observed data set expressed as per cent and is defined by the following equation:

$$D_v = \frac{1}{N}\sum_{i=1}^{N}\frac{h_{si} - h_{oi}}{h_{oi}} \times 100 \qquad \text{... (8)}$$

Nash-Sutcliffe efficiency (NSE)

The Nash-Sutcliffe efficiency is another widely used performance evaluation index for hydrological models and is defined by the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(h_{oi} - h_{si}\right)^2}{\sum_{i=1}^{N}\left(h_{oi} - \overline{h_o}\right)^2} \qquad \text{... (9)}$$

The best-fit between observed and simulated groundwater levels under ideal conditions would yield bias = 0, MAE = 0, SEE = 0, RMSE = 0, normalized RMSE = 0, r = 1, Dv = 0 and NSE =1.

5. Model Calibration

The 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. The transient calibration of the developed model was done 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, 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. For the quantitative evaluation, statistical indicators were considered, and the qualitative evaluation was done by comparing observed and simulated groundwater level hydrographs.

The statistical indicators, i.e., bias, mean absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE, correlation coefficient (r), mean percent deviation (Dv) and Nash-Sutcliffe efficiency (NSE) at nineteen calibration sites are presented in Table 1. The bias values range from a minimum of 0.006 m at Site D and F to a maximum of -0.517 m at Site G, whereas the MAE values range from a minimum of 0.335 m at Site H to a maximum of 0.663 m at Site R. The SEE values range from a minimum of 0.034 m at Site B to a maximum of 0.072 m at R, whereas the RMSE values range from a minimum of 0.442 m at Site D to a maximum value of 0.817 m at Site R. The normalized RMSE values range from a minimum of 8.13% at Site N to a maximum of 15.53% at Site C, whereas the correlation coefficient values range from a minimum of 0.891 at Site G to a maximum of 0.974 at Site J. The Dv values range from a minimum of -0.01% at Site F to a maximum of -3.15% at Site G, whereas the NSE values range from a minimum of 0.602 at Site C to a maximum of 0.918 at Site J. These results indicate that the simulated groundwater levels at sites D, F, H, J and N are more accurate compared to other sites (relatively low values of MAE and RMSE, and high values of r and NSE). On the other hand, there has been relatively inferior simulation of groundwater levels at sites C, E, G and R as the MAE and RMSE values are on a higher side, and r and

Table 1: Model Performance Statistics during Calibration Period

Site	Calibration Period (February 2004 to May 2006)							
	Bias (m)	**MAE (m)**	**SEE (m)**	**RMSE (m)**	**Normalized RMSE (%)**	**r**	**D_v (%)**	**NSE**
A	0.347	0.505	0.043	0.589	11.15	0.944	2.40	0.831
B	-0.490	0.508	0.034	0.616	14.47	0.954	-3.01	0.693
C	-0.267	0.593	0.055	0.660	15.53	0.932	-1.79	0.602
D	0.006	0.344	0.040	0.442	8.29	0.946	0.12	0.895
E	-0.175	0.655	0.067	0.765	14.54	0.918	-1.28	0.700
F	0.006	0.382	0.044	0.485	8.40	0.949	-0.01	0.872
G	-0.517	0.616	0.051	0.768	12.81	0.891	-3.15	0.613
H	0.012	0.335	0.040	0.444	8.49	0.963	0.26	0.907
I	-0.090	0.515	0.058	0.642	11.22	0.925	-0.68	0.792
J	0.117	0.370	0.041	0.472	8.74	0.974	1.07	0.918
K	-0.081	0.496	0.062	0.686	10.60	0.904	-0.60	0.782
L	-0.253	0.462	0.057	0.682	9.98	0.901	-1.79	0.775
M	0.161	0.486	0.055	0.632	8.85	0.937	1.60	0.857
N	0.207	0.399	0.042	0.505	8.13	0.962	1.91	0.900
O	0.142	0.424	0.053	0.599	9.25	0.934	1.17	0.857
P	-0.407	0.449	0.042	0.617	9.45	0.950	-3.10	0.828
Q	0.031	0.397	0.053	0.581	8.55	0.932	0.40	0.861
R	-0.210	0.663	0.072	0.817	11.26	0.923	-1.08	0.809
S	0.273	0.473	0.048	0.600	9.13	0.948	2.56	0.863
Mean	**-0.063**	**0.478**	**0.013**	**0.620**	**6.01**	**0.957**	**-0.27**	**0.915**

NSE values are on a lower side. The bias values at sites B, C, E, G, I, K, L, P and R are negative, which indicates there is overall under-simulation at these sites. There is overall over-simulation at the remaining sites. However, there is an overall good calibration because the values of bias, MAE, SEE, RMSE, normalized RMSE and Dv for almost all the sites are reasonably low and are within acceptable limits. Also, the correlation coefficient and NSE values are reasonably high at most of the sites.

The observed and calibrated groundwater levels at five different sites distributed over the entire area, i.e., Baulakuda (Site A), Gobindpur (Site G), Dhuleswar (Site J), Kalapada (Site O) and Chanduli (Site S) are shown in Figs. 7(a to e), respectively. These figures also indicate a reasonably good match between observed and calibrated groundwater levels at the five sites. The MODFLOW-generated scatter diagram along with 1:1 line, 95% interval lines and 95% confidence interval lines for the entire calibration (pooled data) is shown in Fig. 8. The 95% interval is the interval where 95% of the total number of data points is expected to occur. The 95% confidence interval shows the range of calculated values for each observed value with 95% confidence that the simulation results will be acceptable for a given observed value. For an ideal calibration, the 1:1 line should lie within the 95% confidence interval lines (WHI, 2005). Fig.8 shows that the 1:1 line lies within the 95% confidence interval lines indicating a good calibration of the developed groundwater flow model.

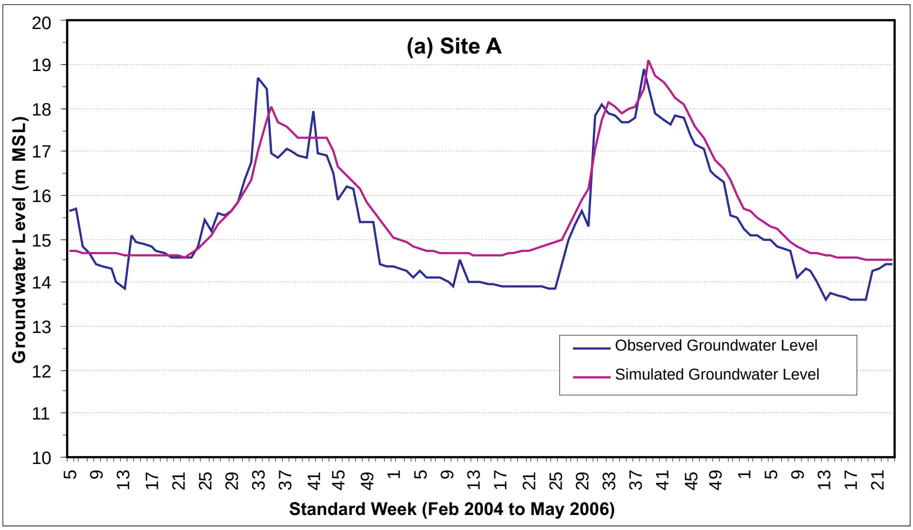


Fig. 7 (a): Comparison between Observed and Simulated Groundwater Levels at Site A for the Calibration Period

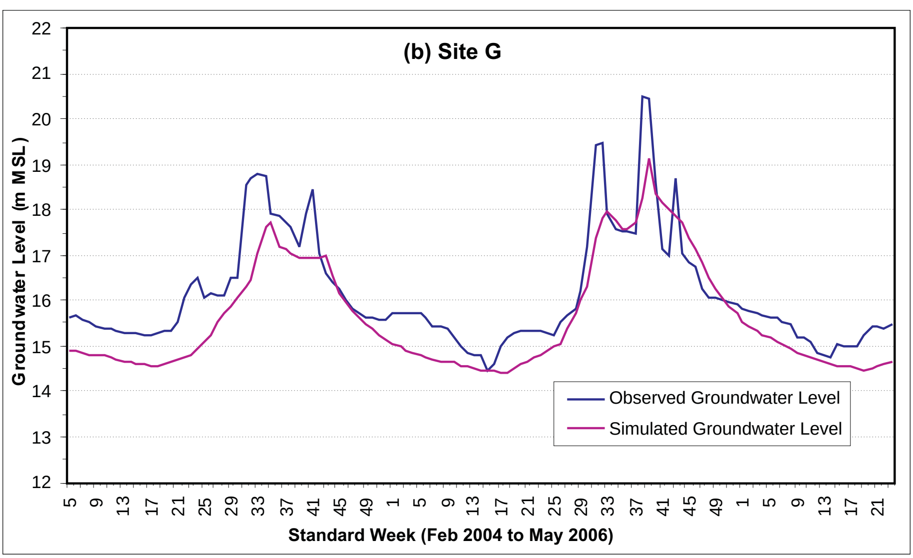


Fig. 7(b): Comparison between Observed and Simulated Groundwater Levels at Site G for the Calibration Period

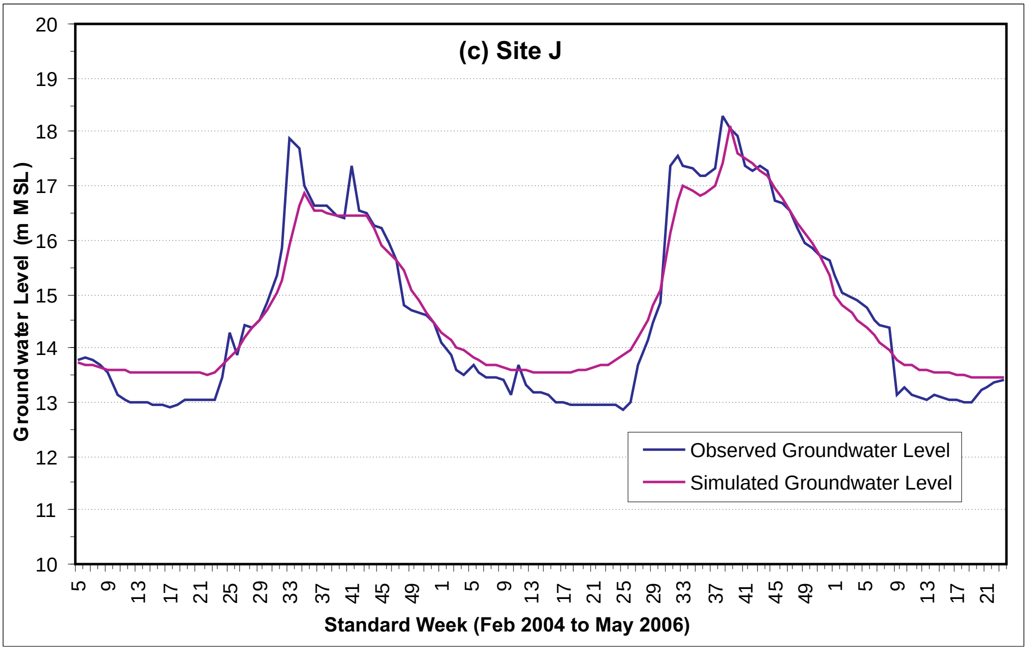


Fig. 7(c): Comparison between Observed and Simulated Groundwater Levels at Site J for the Calibration Period

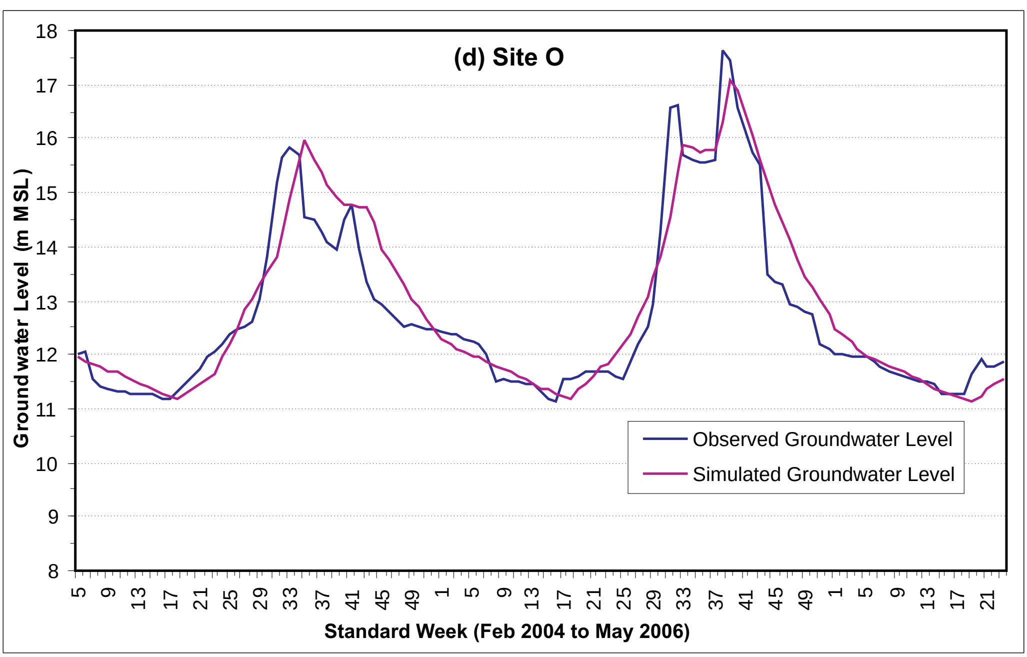


Fig. 7(d): Comparison between Observed and Simulated Groundwater Levels at Site O for the Calibration Period

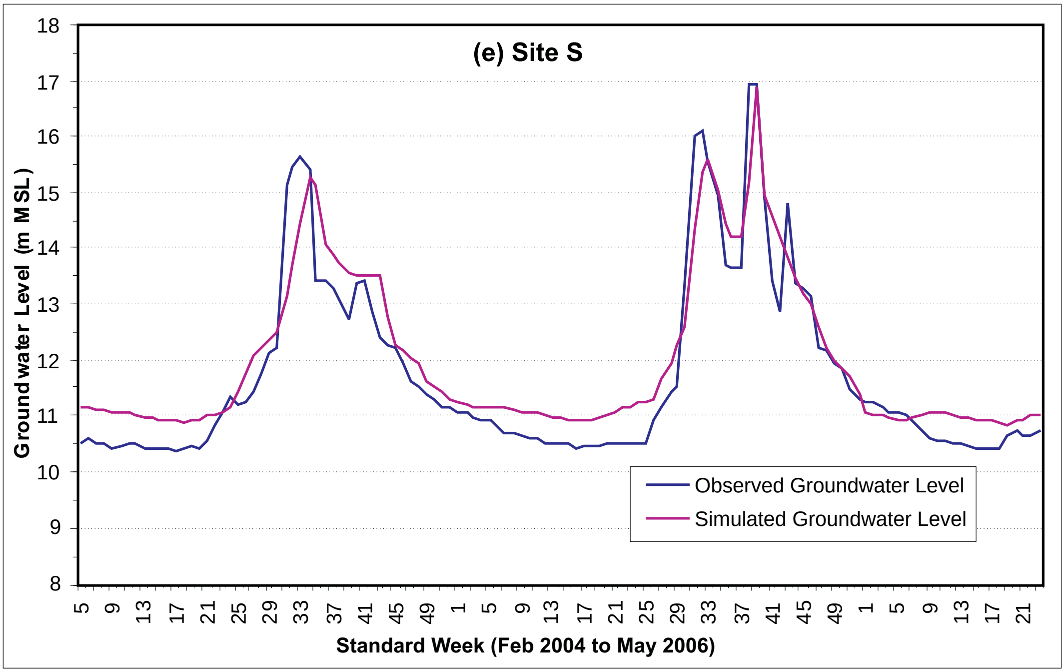


Fig. 7(e): Comparison between Observed and Simulated Groundwater Levels at Site S for the Calibration Period

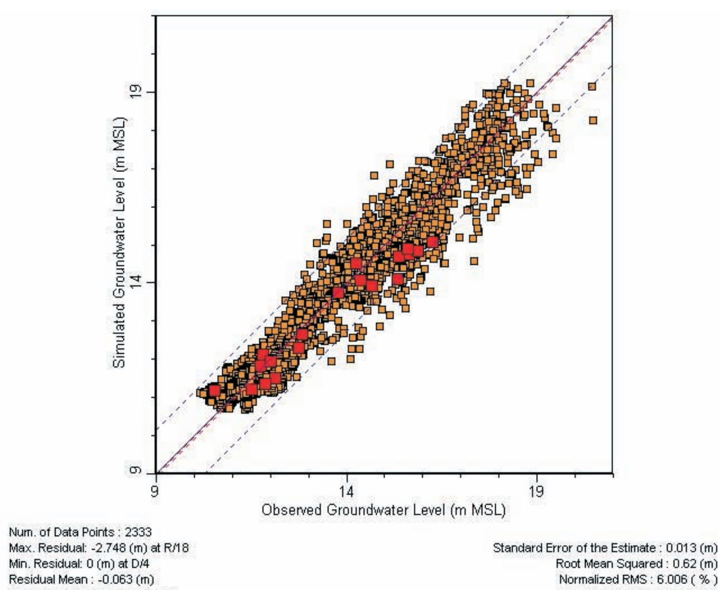


Fig. 8: Scatter Diagram of Observed versus Simulated Groundwater Levels for the Pooled Data during Calibration Period

Table 2 shows the calibrated values of hydraulic conductivity and specific storage of the confined aquifer and 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 (sites A and B) to a maximum of 52 m/day (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/year to 640 mm/year, whereas they vary from 143 mm/year to 175 mm/year in the dry season.

6. Validation of the Model

After calibrating 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. Table 3 presents bias, mean

Table 2: Calibrated Values of the Parameters

Site	K_h (m/day)	S_s	Monthly Average Recharge (mm/year)	
			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**	$\mathbf{1.24 \times 10^{-5}}$	**593.80**	**162.24**

absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), normalized RMSE, correlation coefficient (r), mean percent deviation (Dv) and Nash-Sutcliffe efficiency (NSE) values at 18 sites during validation of the developed groundwater flow model. The bias values range from a minimum of -0.025 m at Site Q to a maximum of -0.505 m at Site P, whereas the MAE values vary from a minimum of 0.297 m at Site Q to a maximum of 0.709 m at Site M. The SEE values range from a minimum of 0.051 m at Site G to a maximum of 0.112 m at Site E, whereas the RMSE values vary from a minimum of 0.38 m at Site Q to a maximum of 0.827 m at Site E. The normalized RMSE values range from a minimum of 6.27% at Site Q to a maximum of 19.51% at Site C, while the correlation coefficient values range from a minimum of 0.922 at Site H to a maximum of 0.982 at Site Q. The Dv values range from a minimum of 0.36% at Site F to a maximum of -3.78% at Site P, 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

Table 3: Model Performance Statistics during Validation Period

Site	Validation Period (June 2006 to May 2007)							
	Bias (m)	MAE (m)	SEE (m)	RMSE (m)	Normalized RMSE (%)	r	D_v (%)	NSE
A	0.473	0.536	0.075	0.717	13.94	0.931	3.16	0.763
B	-0.438	0.568	0.072	0.677	15.54	0.924	-2.62	0.718
C	-0.072	0.657	0.107	0.775	19.51	0.944	-0.66	0.550
D	0.236	0.343	0.060	0.493	9.31	0.955	1.57	0.884
E	0.182	0.658	0.112	0.827	16.25	0.968	0.83	0.670
F	0.082	0.613	0.102	0.737	13.40	0.935	0.36	0.706
G	-0.399	0.436	0.051	0.542	10.37	0.967	-2.40	0.855
H	0.081	0.511	0.090	0.657	12.41	0.922	0.80	0.826
I	0.369	0.529	0.082	0.697	13.75	0.981	2.18	0.775
J	0.124	0.417	0.081	0.600	12.15	0.922	0.95	0.841
K	0.284	0.400	0.058	0.505	8.36	0.973	2.04	0.912
L	-0.277	0.379	0.061	0.522	7.82	0.964	-1.96	0.900
M	0.312	0.709	0.104	0.812	11.39	0.968	3.11	0.843
O	0.369	0.424	0.059	0.563	8.82	0.974	2.79	0.885
P	-0.505	0.520	0.052	0.631	10.19	0.976	-3.78	0.853
Q	-0.025	0.297	0.053	0.380	6.27	0.982	-0.37	0.945
R	-0.279	0.396	0.066	0.552	8.88	0.972	-1.97	0.907
S	0.282	0.416	0.055	0.486	7.71	0.977	2.59	0.922
Mean	**0.044**	**0.489**	**0.020**	**0.632**	**6.53**	**0.958**	**0.37**	**0.914**

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. The bias values at sites B, C, G, L, P, Q and R are negative, which indicates that there is overall under-simulation at these sites and overall over-simulation at the remaining sites. Overall, there is good simulation of groundwater levels because the bias, MAE, SEE, RMSE, normalized RMSE and Dv 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.

Figs. 9(a to e) show the graphical comparison of observed and simulated groundwater levels at five sites distributed over the study area (sites A, G, J, O and S), respectively during the validation period. These figures show that the simulated groundwater levels reasonably match with observed groundwater levels at all sites. The scatter diagram along with 1:1 line, 95% interval lines and 95% confidence interval lines for the entire validation period is shown in Fig. 10. The 1:1 line lies within the 95% confidence interval lines indicating satisfactory validation of the developed groundwater flow model.

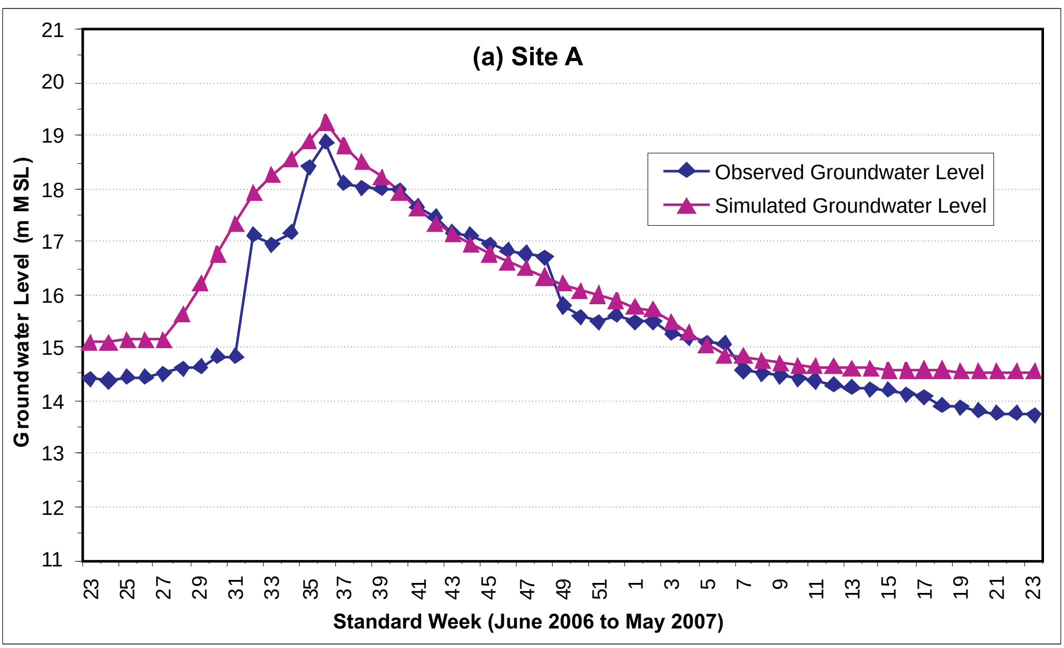


Fig. 9(a): Comparison between Observed and Simulated Groundwater Levels at Site A for the Validation Period

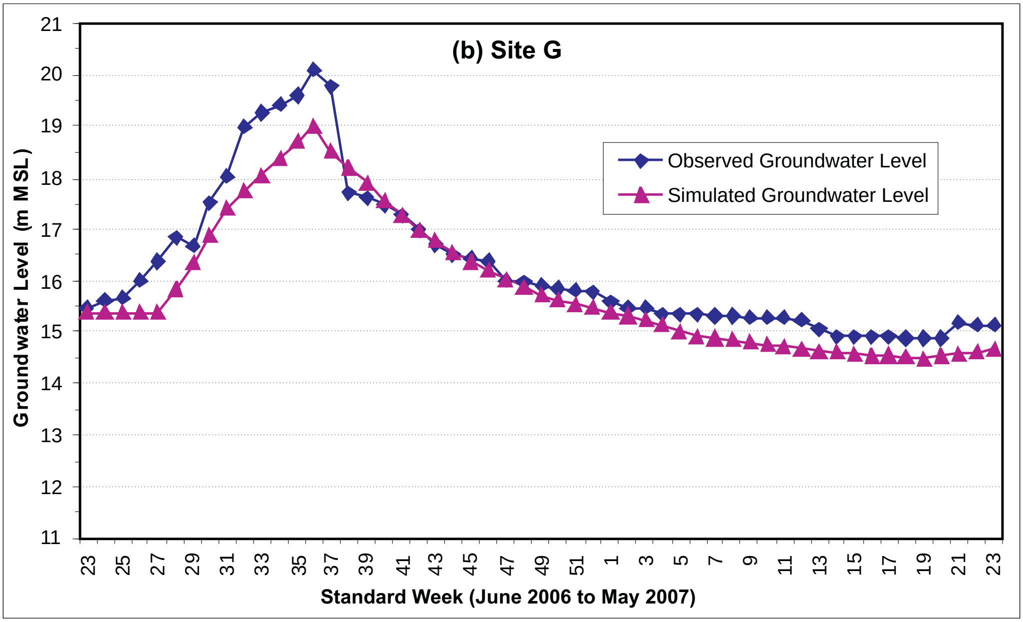


Fig. 9(b): Comparison between Observed and Simulated Groundwater Levels at Site G for the Validation Period

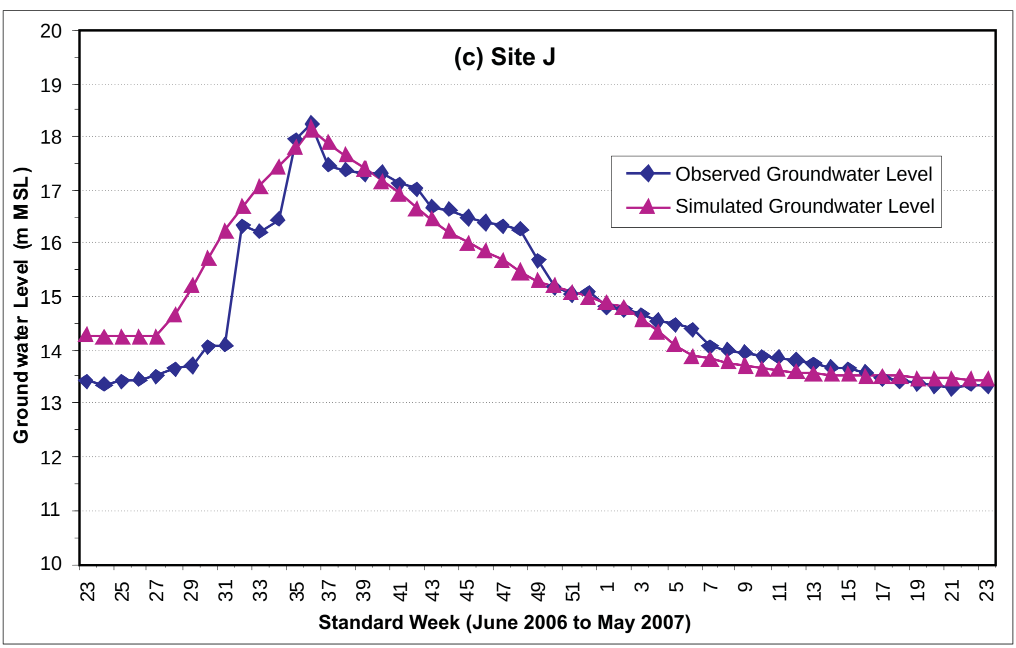


Fig. 9(c): Comparison between Observed and Simulated Groundwater Levels at Site J for the Validation Period

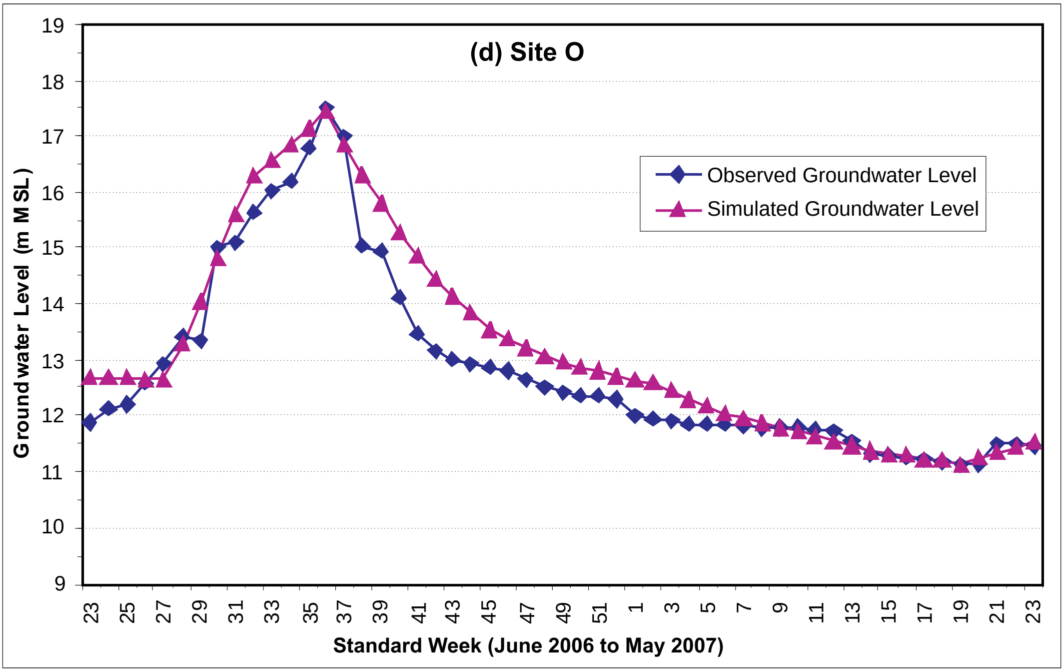


Fig. 9(d): Comparison between Observed and Simulated Groundwater Levels at Site O for the Validation Period

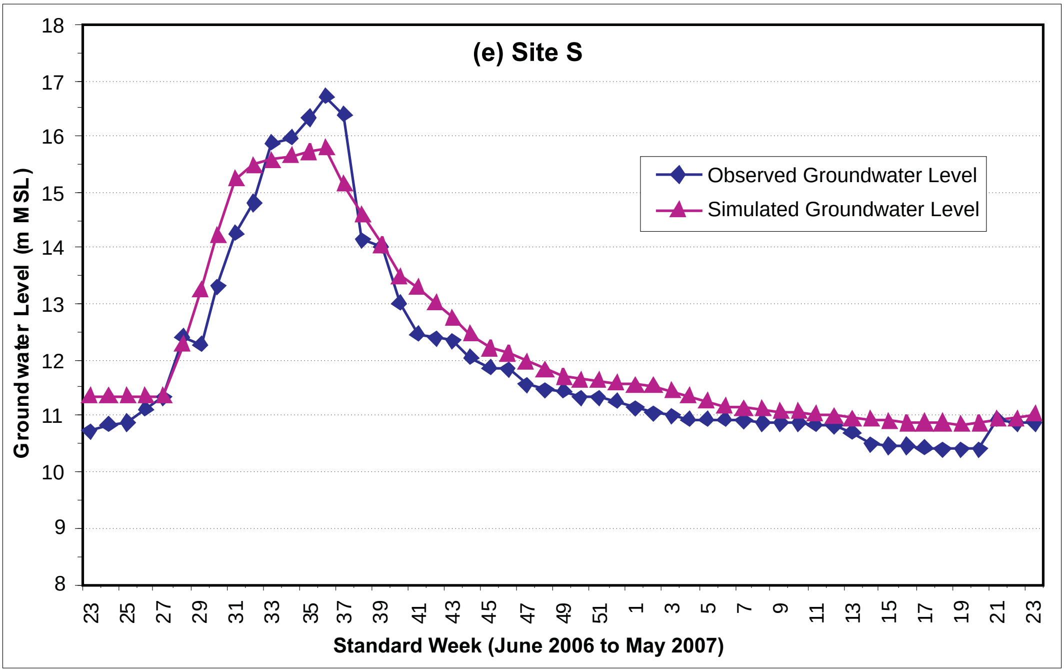


Fig. 9(e): Comparison between Observed and Simulated Groundwater Levels at Site S for the Validation Period

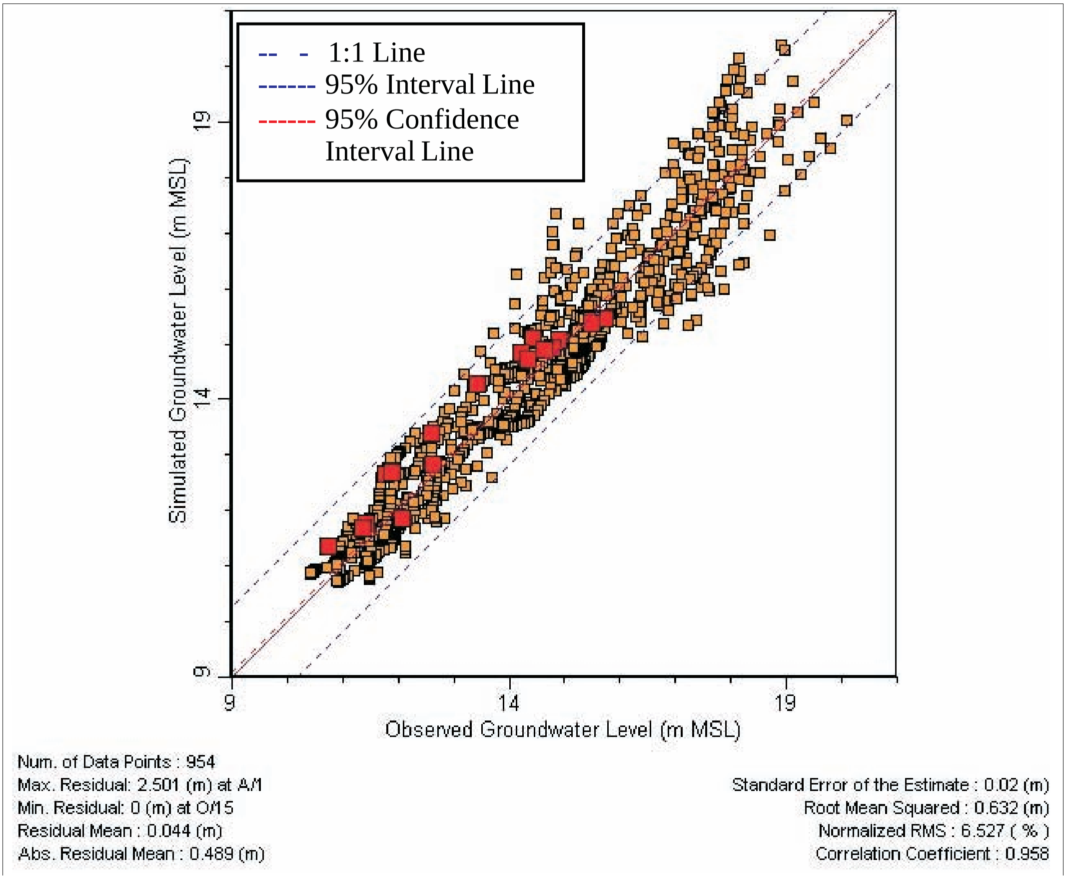


Fig. 10: Scatter Diagram of Observed versus Simulated Groundwater Levels for the Pooled Data during Validation Period

7. Groundwater Scenario in Dry and Wet Seasons

Fig. 11 shows a simulated groundwater-level contour map of the study area for the representative dry season. Similarly, Fig. 12 shows simulated groundwater-level contour map of the study area for the representative wet season. It is evident from Fig. 11 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 groundwater 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

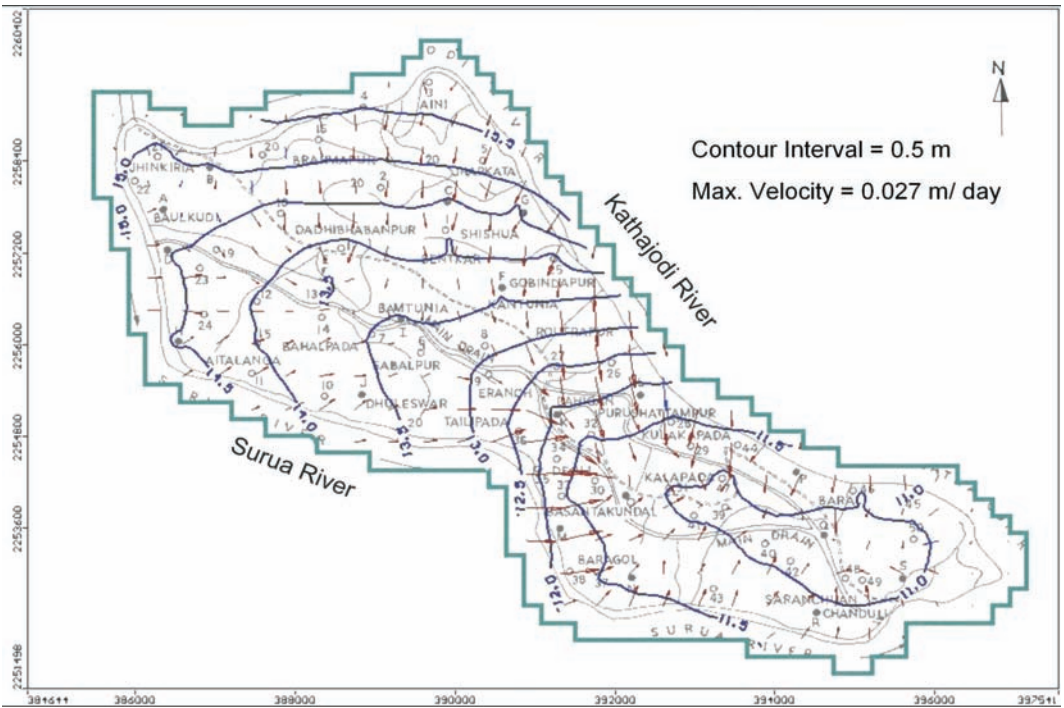


Fig. 11: Groundwater Level Contour Map of a Representative Dry Season with Groundwater Flow Vectors

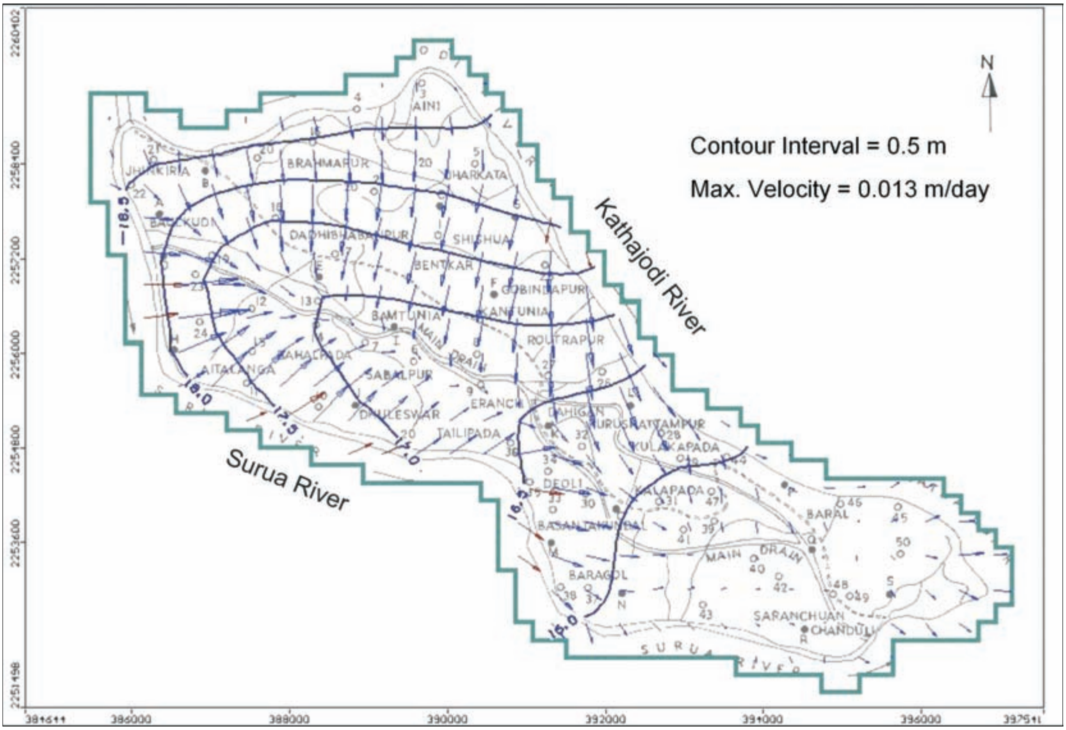


Fig. 12: Groundwater Level Contour Map of a Representative Wet Season with Groundwater Flow Vectors

contour map of the dry season (Fig. 11) 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. 12) 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 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.

8. Sensitivity Analysis

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.

The sensitivity of the model results with respect to model parameters like hydraulic conductivity (K), specific storage (Ss) and recharge at three sites, i.e., Baulakuda (Site A) in the upstream portion of the basin, Dahigan (Site K) in the middle portion of the basin and Chanduli (Site S) in the downstream portion of the basin are shown in Figs. 13(a to c), respectively. These figures indicate 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. Figs. 14 (a to c) show the sensitivity of the model results with respect to river-bed conductivity and river stage at three sites, i.e., Baulakuda (Site A) in the upstream side of the basin, Dahigan (Site K) in the middle of the basin and Chanduli (Site S) in the downstream side of the basin. These figures indicate 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 groundwater levels in alluvial aquifer systems. This finding suggests that the river stage should be measured with high precision compared to the river-bed conductivity so as to ensure reliable model predictions.

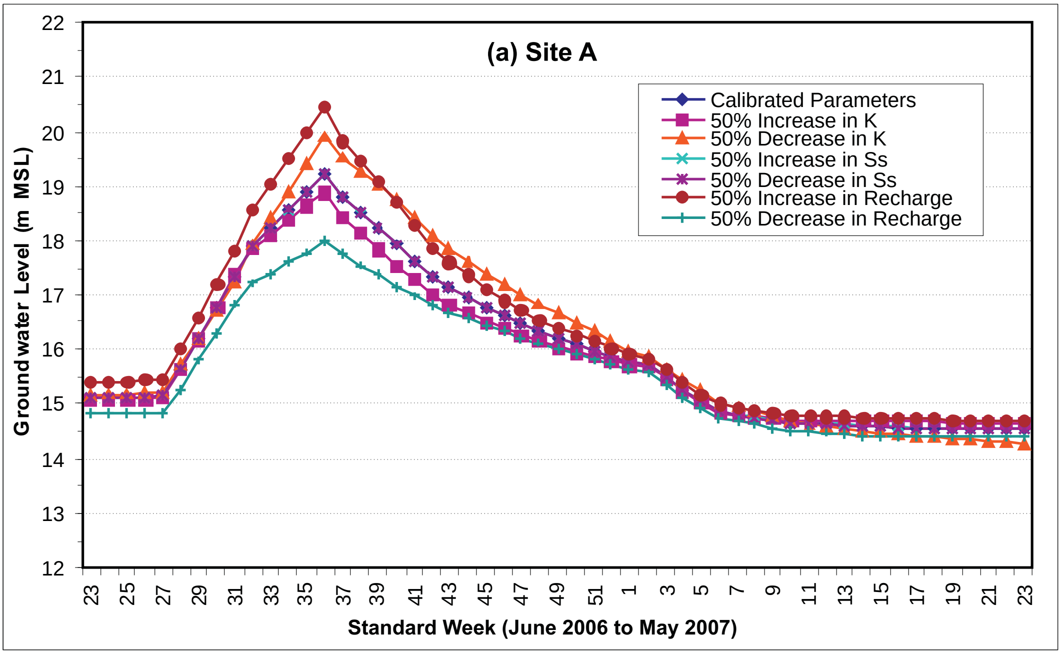


Fig. 13(a): Sensitivity of the Model to the Hydraulic Conductivity, Specific Storage and Recharge at Site A

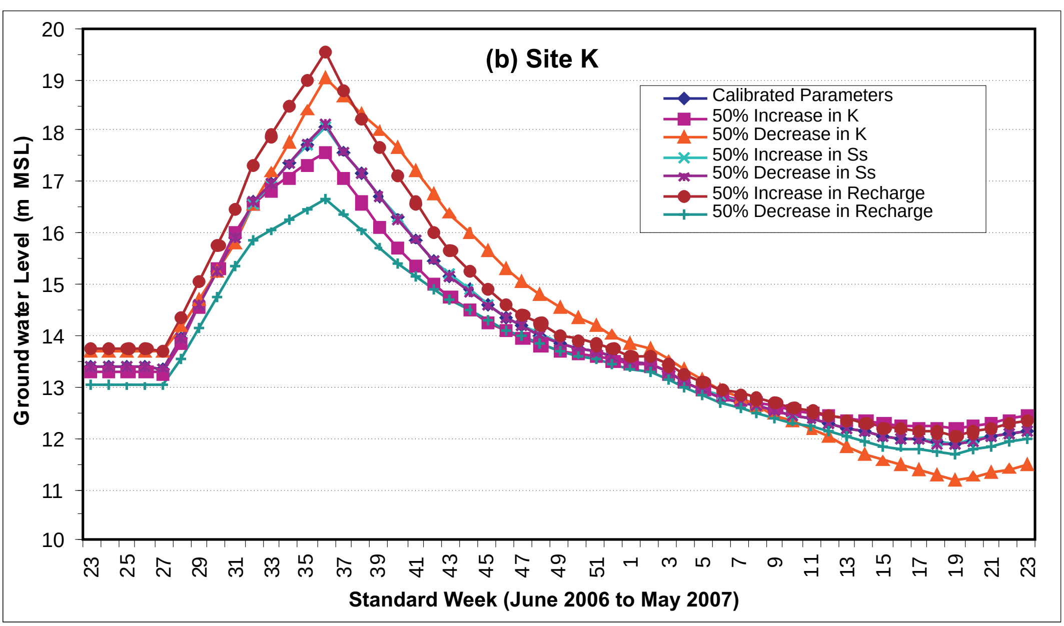


Fig. 13(b): Sensitivity of the Model to the Hydraulic Conductivity, Specific Storage and Recharge at Site K

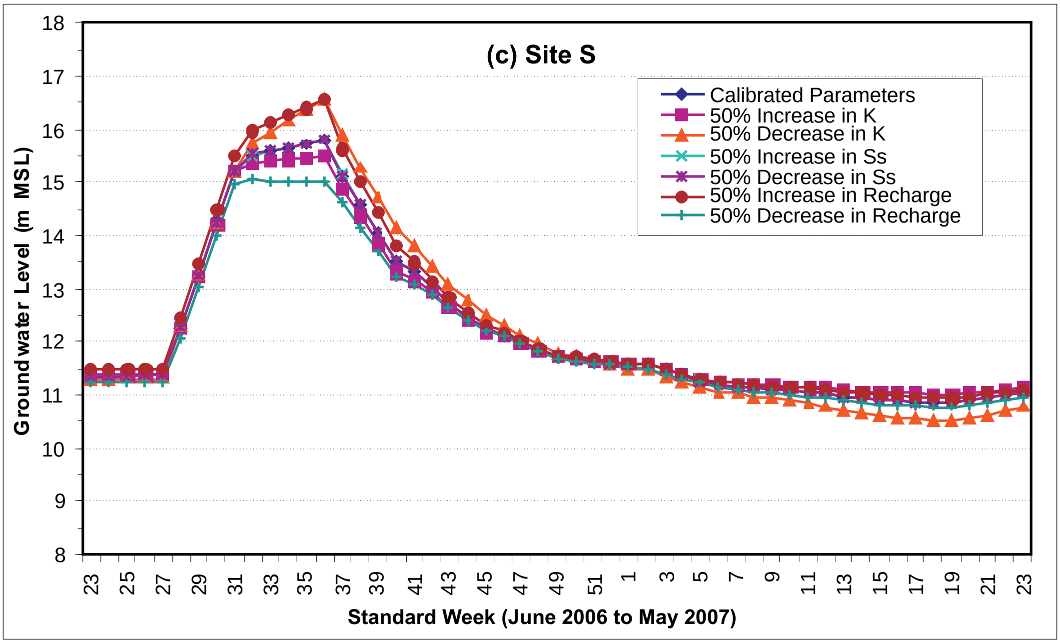


Fig. 13(c): Sensitivity of the Model to the Hydraulic Conductivity, Specific Storage and Recharge at Site S

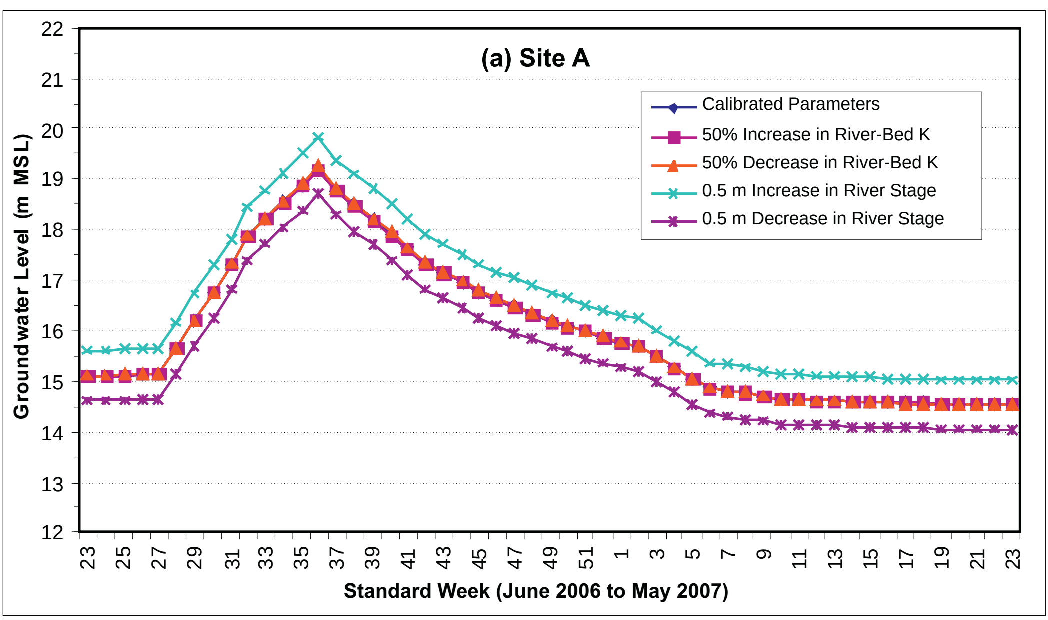


Fig. 14 (a): Sensitivity Analysis of River-Bed Conductivity and River Stage on Groundwater Level at Site A

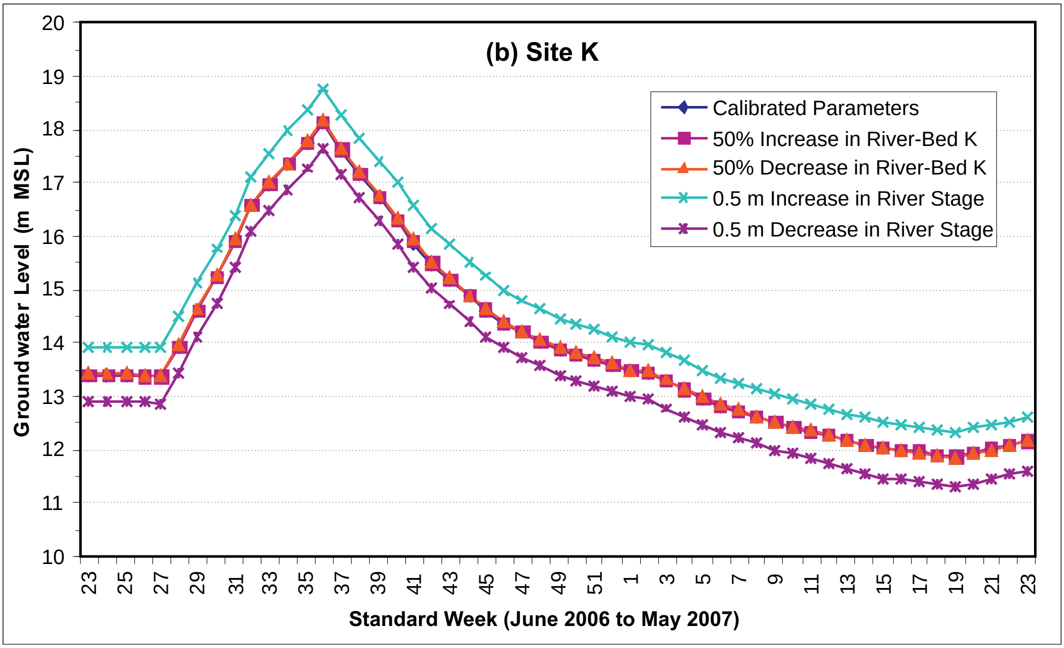


Fig. 14 (b): Sensitivity Analysis of River-Bed Conductivity and River Stage on Groundwater Level at Site K

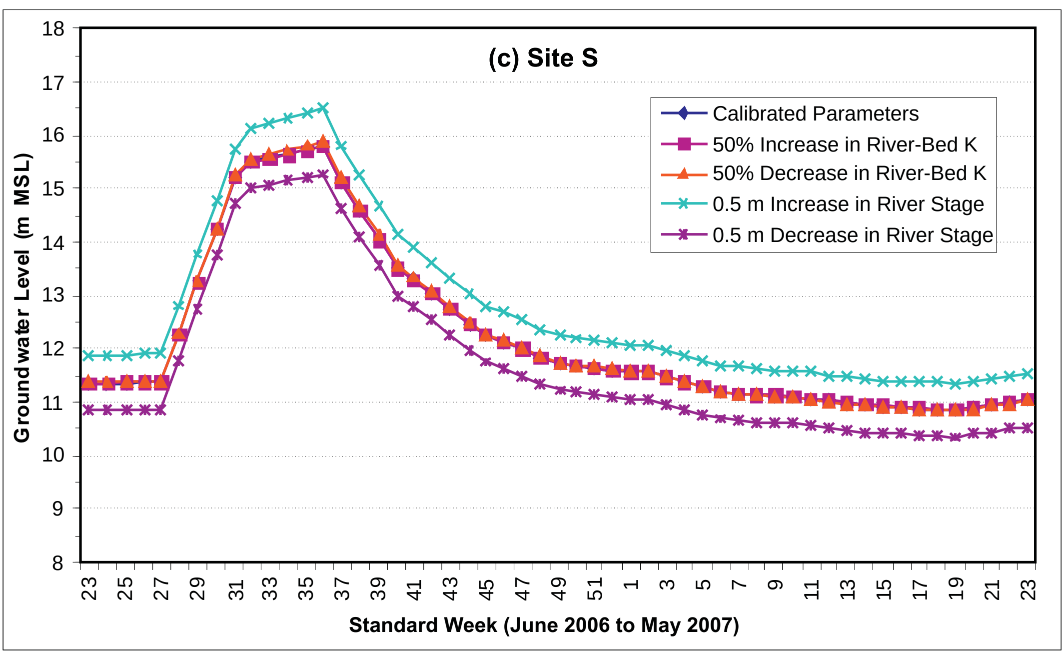


Fig. 14 (c): Sensitivity Analysis of River-Bed Conductivity and River Stage on Groundwater Level at Site S

9. Prediction of Salient Groundwater Scenarios

The calibrated and validated model can be used for a variety of management and planning studies (Anderson and Woessner, 1992; Rushton, 2003; Zheng and Bennett, 2010). Predictive simulations were performed to examine the response of the aquifer to different pumping levels and to simulate groundwater 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. The response of the aquifer to increased/decreased pumping, i.e., 50% (50% decrease), 75% (25% decrease), 100% (status-quo), 125% (25% increase) and 150% (50% increase) of the existing pumping rates at the three sites, i.e., Baulakuda (Site A) in the upstream side of the basin, Dahigan (Site K) in the middle of the basin and Chanduli (Site S) in the downstream side of the basin is shown in Figs. 15(a to c), respectively. It is evident from the figures that the increase or decrease in pumping rates up to 50% has not resulted in any significant changes in the groundwater levels during the weeks 30-50, which mostly coincides with the wet season. The changes in groundwater level are more pronounced in dry 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.

(b) Scenario 2: Groundwater scenario during 2007-2020 period under existing pumping conditions

Under this scenario, keeping all the existing conditions constant, the effect of continuation of existing pumpage on groundwater levels during 2007-2020 period was examined. Fig. 16 shows 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) during the period (2007-2020), keeping all the parameters constant. It is clear that there is no significant change in groundwater levels up to the year 2020 at all the sites. The groundwater levels at sites O and S are relatively lower than the other 3 sites, and that scenario is maintained 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

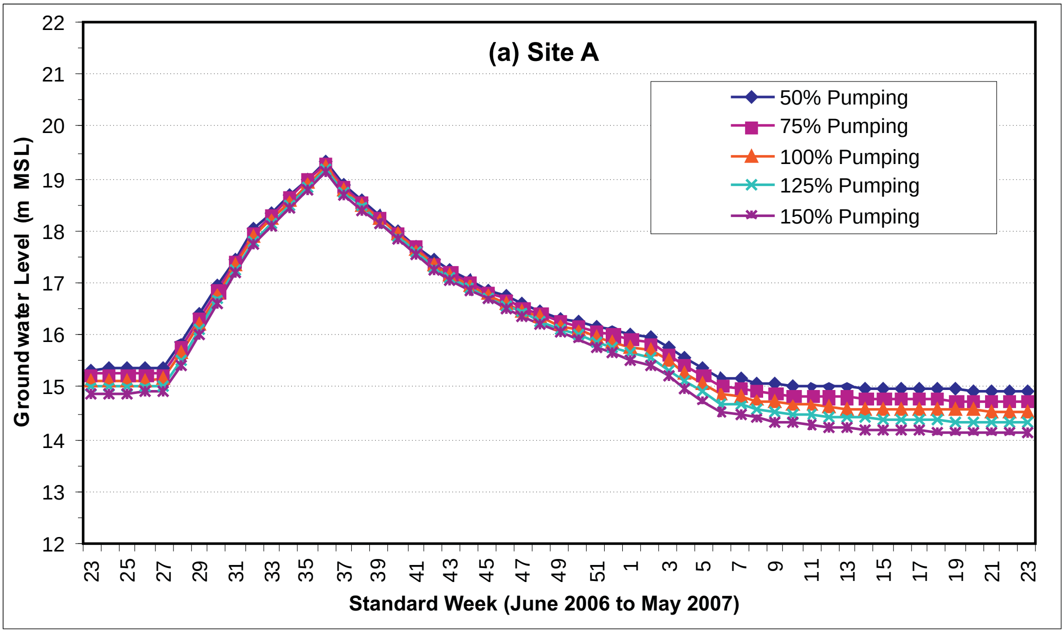


Fig. 15 (a): Groundwater Scenario at Site A under 50, 75, 100, 125 and 150% Pumpage Conditions

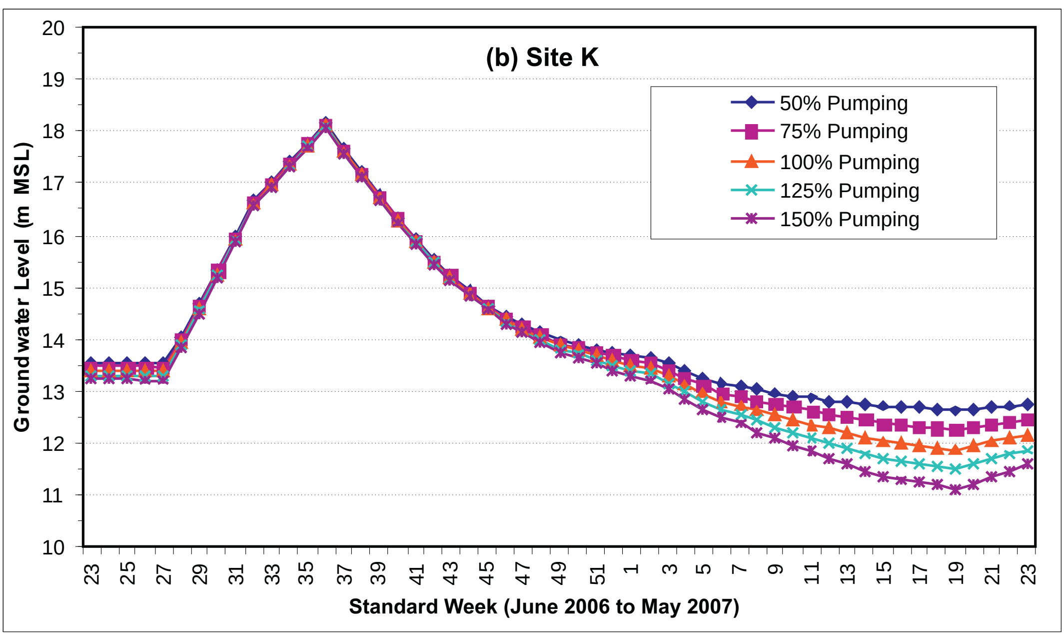


Fig. 15 (b): Groundwater Scenario at Site K under 50, 75, 100, 125 and 150% Pumpage Conditions

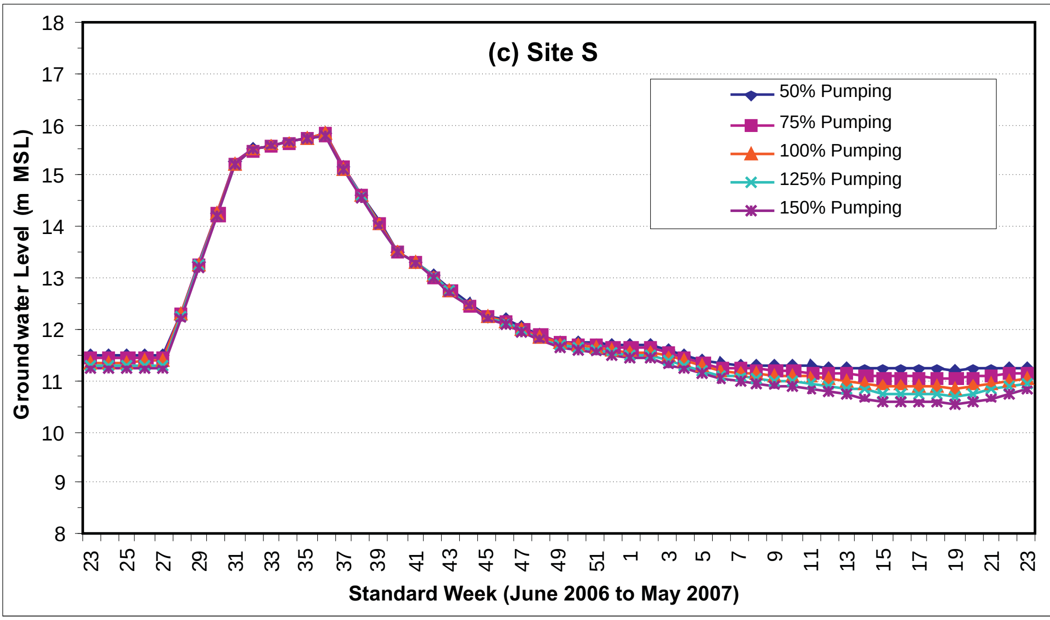


Fig. 15 (c): Groundwater Scenario at Site S under 50, 75, 100, 125 and 150% Pumpage Conditions

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 (by 2020). Thus, if the existing conditions continue, there is no threat to the groundwater lowering in the study area in the near future.

10. Conclusions

A groundwater flow simulation model was developed for the Kathajodi-Surua Inter-basin using Visual MODFLOW model for simulating groundwater scenarios. An extensive weekly groundwater monitoring program was initiated in the study area. A combination of trial and error technique and automated calibration code PEST was used to calibrate the model in which parameters hydraulic conductivity, storage coefficient and recharge were adjusted to achieve the calibration target. A reasonably good match between the observed and simulated groundwater levels was observed during both calibration and validation period. The sensitivity analysis results showed that the groundwater level was more sensitive to river stage followed by

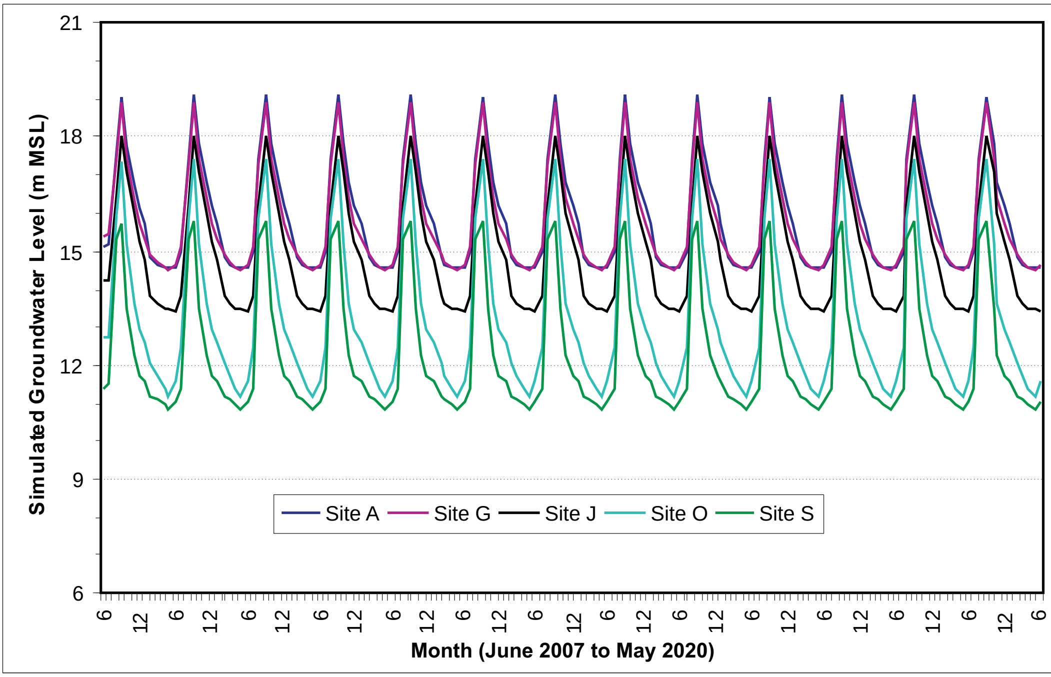


Fig. 16: Simulated Groundwater Levels during the Period 2007-2020

recharge and hydraulic conductivity whereas it was least sensitive to changes in specific storage. Increase or decrease in pumping rates had an effect on corresponding decrease or increase in groundwater level, especially in rainy season. Keeping all the existing conditions constant, the effect of continuation of present pumping on groundwater level upto the year 2020 was examined. There was no significant change in groundwater level even upto the year 2020. The Kathjodi-Surua Inter-basin being a complete river island surrounded by two rivers on both sides, the pumped water is replenished by seepage from river. Therefore, there is no threat to groundwater level in Kathjodi-Surua Inter-basin in the near future. The study has been useful in understanding the groundwater dynamics of the study area, and thereby effective in developing groundwater management strategy in the region. The methodology demonstrated in this study being generic in nature, will also be useful for other river basins of the country.

References

Ahmed, I. and Umar, R. (2009). Groundwater flow modeling of Yamuna-Krishni interstream, a part of central Ganga Plain, Uttar Pradesh. Journal of Earth System Science, 118(5): 507-523.

Anderson, M.P. and Woessner, W.W. (1992). Applied Groundwater Modeling – Simulation of Flow and Advective Transport. Academic Press Inc., California.

Bear, J. and Cheng, A.H.D. (2010). Modeling Groundwater Flow and Contaminant Transport. Springer, Dordrecht, The Netherlands.

Biswas, A. K. (1992). Sustainable water development: a global perspective. Water International, 17(2): 68-80.

CGWB (2011). Dynamic Groundwater Resources of India (as on March, 2009). Central Ground Water Board (CGWB), Ministry of Water Resources, New Delhi, India.

Doll, P. and Siebert, S. (2001). Global Modeling of Irrigation Water Requirement, University of Kassel, Kassel, Germany.

Elango, L., Brindha, K., Kalpana, L., Sunny, F., Nair, R.N. and Murugan, R. (2012). Groundwater flow and radionuclide decay-chain transport modeling around a proposed uranium tailings pond in India. Hydrogeology Journal, 20: 797-812.

Falkenmark, M. and Lundqvist, J. (1997). World Freshwater Problems- Call for a new Realism, UN/SEI, New York/ Stockholm.

Hiscock, K.M., Rivett, M.O. and Davison, R.M. (editors) (2002). Sustainable Groundwater Development. Special Publication No. 193, Geological Society, London, U.K.

Jha, M.K., Kamii, Y. and Chikamori, K. (2001). Irrigation and water management: An Indian perspective. Rural and Environmental Engineering, 40(2): 46-66.

Kumar, R., Singh, R.D. and Sharma, K.D. (2005). Water resources of India. Current Science, 89(5): 794-811.

Mall, R.K7., Gupta, A., Singh, R., Singh, R.S. and Rathore, L.S. (2006). Water resources and climate change: An Indian perspective. Current Science, 90(12): 1610-1626.

Raul, S., Panda, S.N., Hollander, H. and Billib, M. (2011). Integrated water resources management in a major canal command in eastern Inida. Hydrological Processes, 25: 2551-2562.

Rodda J. C. (1992). Water, the ultimate dilemma for environment and development. Ecodecision, pp 25-29.

Rushton, K.R. (2003). Groundwater Hydrology: Conceptual and Computational Models. John Wiley and Sons, Chichester, U.K., 416 pp.

WHI (2005). Visual Modflow Professional Edition User's Manual. Waterloo Hydrogeologic Inc., Ontario, Canada, 611 pp.

Zheng, C. and Bennett, G.D. (2002). Applied Contaminant Transport Modeling. 2nd Edition, John Wiley & Sons, Inc., New York.

Zume, J. and Tarhule, A. (2008). Simulating the impacts of groundwater pumping on stream-aquifer dynamics in semi-arid north-western Oklahoma, USA. Hydrogeology Journal, 16: 797-810.