

Numerical groundwater-flow modeling to evaluate potential effects of pumping and recharge: implications for sustainable groundwater management in the Mahanadi delta region, India

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Abstract Process-based groundwater models are useful to understand complex aquifer systems and make predictions about their response to hydrological changes. A conceptual model for evaluating responses to environmental changes is presented, considering the hydrogeologic framework, flow processes, aquifer hydraulic properties, boundary conditions, and sources and sinks of the groundwater system. Based on this conceptual model, a quasi-three-dimensional transient groundwater flow model was designed using MODFLOW to simulate the groundwater system of Mahanadi River delta, eastern India. The model was constructed in the context of an upper unconfined aquifer and lower confined aquifer, separated by an aquitard. Hydraulic heads of 13 shallow wells and 11 deep wells were used to calibrate transient groundwater conditions during 1997–2006, followed by validation (2007–2011). The aquifer and aquitard hydraulic properties were obtained by pumping tests and were calibrated along with the rainfall recharge. The statistical and graphical performance indicators suggested a reasonably good simulation of groundwater flow over the study area. Sensitivity analysis revealed that groundwater level is most sensitive to the hydraulic conductivities of both the aquifers, followed by vertical hydraulic conductivity of the confining layer. The calibrated model was then employed to explore groundwater-flow dynamics in re-

sponse to changes in pumping and recharge conditions. The simulation results indicate that pumping has a substantial effect on the confined aquifer flow regime as compared to the unconfined aquifer. The results and insights from this study have important implications for other regional groundwater modeling studies, especially in multi-layered aquifer systems.

Keywords Groundwater flow · Conceptual models · Sensitivity analysis · MODFLOW · India

Introduction

Groundwater—the largest source of freshwater on the Earth—is an immensely important natural resource for energy and food security, human health and ecosystems. Unfortunately, mismanagement of this valuable resource has led to questions regarding its sustainability, thereby creating serious groundwater depletion and environmental problems for both present and future generations (Vrba et al. 2007; Rodell et al. 2009; Konikow 2011; Döll et al. 2012; Van der Gun 2012; Taylor et al. 2013; Mays 2013; Wada et al. 2014; Gleeson et al. 2016). Therefore, there is greater emphasis now on strategic and optimal utilization of groundwater resources to combat mounting freshwater demand in the future. India is the largest user of groundwater in the world with an estimated withdrawal of 230 km³/year, which is over a quarter of the global total (World Bank 2010). More than 60% of the irrigated agriculture and 85% of the drinking-water supplies are dependent on groundwater. On average, between 2000 and 2001 and 2006–2007, about 61% of the irrigation in the country was sourced from groundwater, while the contribution of surface water has declined from 60% in the 1950s to 30% in the first decade of the twenty-first century. If the current trend continues, in 20 years, about 60% of India's aquifers will be in a critical

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condition (World Bank 2010). On top of that, climatic variations and socio-economic changes are expected to aggravate water problems in the country. Such a water situation will have serious implications for the sustainability of agriculture, long-term food availability, water and energy securities, livelihoods, and economic growth of the country.

Despite having abundant natural resources, Odisha, an eastern state of India, has been facing numerous water-related problems. Major issues include drinking water crisis, unregulated use of irrigation water, high soil erosion and sedimentation in the major river basins, lowering of groundwater levels, groundwater contamination, changes in the pattern of rainfall, and, above all, natural calamities like flood, drought, and cyclones (Panda et al. 2007; Rejani et al. 2008). According to the latest assessment in March 2011, the total annual replenishable groundwater resource of Odisha is 17.78 km³, of which rainfall recharge contributes about 71% and the contribution from other sources such as canal seepage, return flow from irrigation, seepage from water bodies, etc., is 29% (CGWB 2014). Net annual groundwater availability in Odisha is 16.69 km³, out of which groundwater withdrawal for irrigation is highest (81% of total annual groundwater draft). According to the Central Ground Water Board (CGWB 2014), groundwater development in Odisha is only 28%, implying that there is great scope for groundwater development in the state. Poor infrastructure facilities, fragmented land holdings coupled with traditional cropping patterns, unreliable power supply in remote areas, and higher energy requirement to extract groundwater are some of the constraints for optimal development of groundwater in Odisha (Srivastava et al. 2013). Therefore, a detailed understanding of groundwater dynamics, diverse hydrogeologic settings and agro-climatic conditions is imperative for sustainable management of groundwater resources in the state.

Groundwater simulation models have emerged as a powerful tool for addressing complex real-world problems and issues concerning impacts of extensive groundwater development as well as of other developmental activities (Anderson and Woessner 1992; Rushton 2003; Kresic 2006; Bear and Cheng 2010). These models are useful in simulating groundwater flow or contaminant scenarios under different management options, thereby enabling authorities to take corrective/remedial measures for the efficient utilization of water resources as well as for the protection of ecosystems. The simulation approach attempts to capture key elements of real-world complexity by integrating the components of a physical hydrogeologic system, climatic effects, and anthropogenic stresses, thereby providing insights not only into changes within the aquifer system but also into its interaction with overlying surface water systems (e.g., Wang and Anderson 1982; Willis and Yeh 1987; Zheng and Bennett 2002; Hill and Tiedeman 2007; Jha and Sahoo 2015).

Given the complexity and heterogeneity of aquifer systems, numerical modeling is a powerful method to integrate different data and to evaluate the regional groundwater dynamics as compared to empirical models (Konikow and Kendy 2005; Refsgaard et al. 2012; Sahoo and Jha 2013, 2015). Numerical modeling of groundwater systems has attracted substantial attention worldwide. Major applications include, for example: water resources management (e.g., Peralta et al. 1995; Bauer et al. 2006; Rejani et al. 2008; Refsgaard et al. 2010; Mohanty et al. 2013; El Alfy 2014), sustainability assessment (e.g., Cao et al. 2013), assessment of aquifer conditions under future climate change (e.g., Scibek et al. 2007; Maxwell and Kollet 2008), stream-aquifer interaction (e.g., Chen and Shu 2002; Zume and Tarhule 2008), irrigation management (e.g., Mao et al. 2005; Jang et al. 2016), groundwater overextraction (e.g., Alfaro et al. 2017), land subsidence (e.g., Larson et al. 2001), and seawater intrusion in coastal aquifers (e.g., Sherif et al. 2011). Although various groundwater models are available, MODFLOW, developed by Harbaugh and McDonald (1996) or its modified version has been extensively used for quantifying changes in groundwater flow attributed to recharge, pumping and hydraulic properties of the aquifer (Zhou and Li 2011).

The main purposes for undertaking this study are twofold. First, to date, no comprehensive groundwater flow model has been available that encompasses the majority of the Kushabhadra-Bhargavi basin of the Mahanadi River delta. This is the first time that groundwater-flow dynamics have been simulated across this basin with an overall aim to understand the behavior of the groundwater system, and to formulate sustainable groundwater management scenarios under different conditions of pumping and recharge. Second, no hydraulic property values or conceptual models are readily available for this aquifer system; hence, pumping tests were conducted as a part of this study to estimate hydraulic properties and to build a conceptual model of the system based on available lithologic information. Also, for the first time, this study demonstrates the application of a method proposed by Hemker and Maas (1987) to determine the detailed hydraulic parameters (from the pumping test data) of the wells tapping more than one aquifer layer. Spatial and temporal variability of recharge have also been taken into account by using point-scale estimates from the Visual HELP model. This study also includes sensitivity analysis of the developed model in order to identify influential input parameters in simulating groundwater flow.

Keeping the preceding points in view, a quasi-three-dimensional (3D) groundwater-flow simulation model (horizontal flow within the confining unit is ignored) has been developed for the multi-aquifer system of Kushabhadra-Bhargavi interbasin, in Odisha. Overall, the modeling steps involved: creation of a hydrogeologic framework, development of a conceptual model, estimation of groundwater

recharge, calibration of aquifer parameters, sensitivity analysis of model inputs, application of the model to compute the effect of altered groundwater withdrawal and recharge, and, finally, future projection to evaluate the long-term effects of existing conditions on the groundwater system.

Study area

The Kushabhadra-Bhargavi interbasin is situated in Odisha, a state in the eastern coast of the India and is a part of Mahanadi River delta (Fig. 1a). It is bounded to the east by Kushabhadra River, to the west by Bhargavi River and to the south by Bay of Bengal, with a geographical area of 620 km². The interbasin has been formed by the splitting of the River Kuakhai into Kushabhadra River and Bhargavi River, spreading mostly in the Puri and Khordha districts. The topography of the area is almost flat with elevation varying from 0 to 26 m relative to mean sea level (MSL). The climate of the study area is tropical, characterized by high temperature, high humidity, medium to high rainfall, and short and mild winters. Most of the rainfall received in the region is concentrated over a period from mid-June to end of October with an average annual rainfall of 1,416 mm (Fig. 1b). The mean monthly maximum and minimum temperatures in the area are 42 °C (May) and 17 °C (December).

The study area is mostly occupied by the laterite and alluvium geologic formations (Sahoo et al. 2015). It is underlain by an unconfined aquifer system at shallow depth and a confined aquifer system at relatively deeper depths. The static (pre-pumping) hydraulic head in the shallow aquifer varies between 1 to 7.6 m below ground surface (bgs). The water table in the unconfined aquifer ranges from 1.02 to 8.74 m bgs in the pre-monsoon season and 0.98 to 7.14 m bgs in the post-monsoon season. On the other hand, the piezometric surface of the confined aquifer varies from 0.68 to 9.05 m bgs in the pre-monsoon season and 0.18 to 8 m bgs in the post-monsoon season. The significant seasonal groundwater-level fluctuations in the study area indicate appreciable recharge to the aquifer during monsoon season. These aquifer systems of the Mahanadi delta offer key sources of freshwater in the study area. Groundwater in this region is mainly used for domestic and irrigation purposes through dug wells and tube wells (shallow or deep). Some parts of the region show waterlogging conditions during monsoon and post-monsoon periods due to the prevailing topographic conditions, hydraulic gradient and poor drainage. On the other hand, during the pre-monsoon (dry) period, existing canal systems are not able to supply enough water to support highly irrigated crops even with a modernized conveyance and distribution system; thus, water scarcity problems are more pronounced during dry seasons, as groundwater becomes the only dependable source of water supply in these conditions. Hence, there is a need for

integrated management of surface water and groundwater to prevent water scarcity problems either by storing excess surface water or through groundwater recharge.

Materials and methods

Data acquisition

The daily rainfall data of six rainfall stations (Fig. 1b) were collected for 1990–2011 from the Department of Agriculture, Puri, Odisha. The daily river-stage observations (Fig. 1b) from 1990 to 2011, and other river data such as riverbed thickness, elevation and conductivity, were obtained from the Central Water Commission (CWC), and the Department of Hydrometry, Bhubaneswar, Odisha. The meteorological data of Bhubaneswar and Puri stations such as relative humidity, wind speed, duration of sunshine hours and maximum and minimum air temperatures were collected for 2000–2010 period from the India Meteorological Department, Pune. Hydraulic heads of 13 observation wells tapping the unconfined aquifer (aquifer-1) and 11 observation wells tapping the confined aquifer (aquifer-2; Fig. 1b) were collected for 1997–2011 from the Central Ground Water Board (CGWB) and Ground Water Survey and Investigation (GWS&I), Bhubaneswar, Odisha. The discharge data of 77 pumping wells (Fig. 2) and lithological data (Sahoo and Jha 2016) were acquired from the Odisha Lift Irrigation Corporation (OLIC) and Rural Water Supply and Sanitation (RWSS), Bhubaneswar, Odisha.

Development of the groundwater-flow model: conceptual model

A quasi-3D transient groundwater-flow model was developed for the three-layered system of the study area. In this quasi-3D model, horizontal flow within the confining unit is ignored and heads in the confining units are not calculated. The effect of the confining unit is simulated by means of a leakage term representing vertical flow between two aquifers (Anderson and Woessner 1992). This numerical model was developed and calibrated using the standard procedures of groundwater modeling, which is commonly known as “modeling protocol” and it was first reported by Anderson and Woessner (1992). The finite-difference based Visual MODFLOW-2000 software (WHI 2006) was used to construct the model and to perform simulation analysis. The systematic model design, development, and application are discussed.

A conceptual model of the Kushabhadra-Bhargavi interbasin was developed in this study to analyze the groundwater system in the study area and to develop input datasets for the numerical flow model. A brief description of the hydrogeologic analysis, boundary conditions and

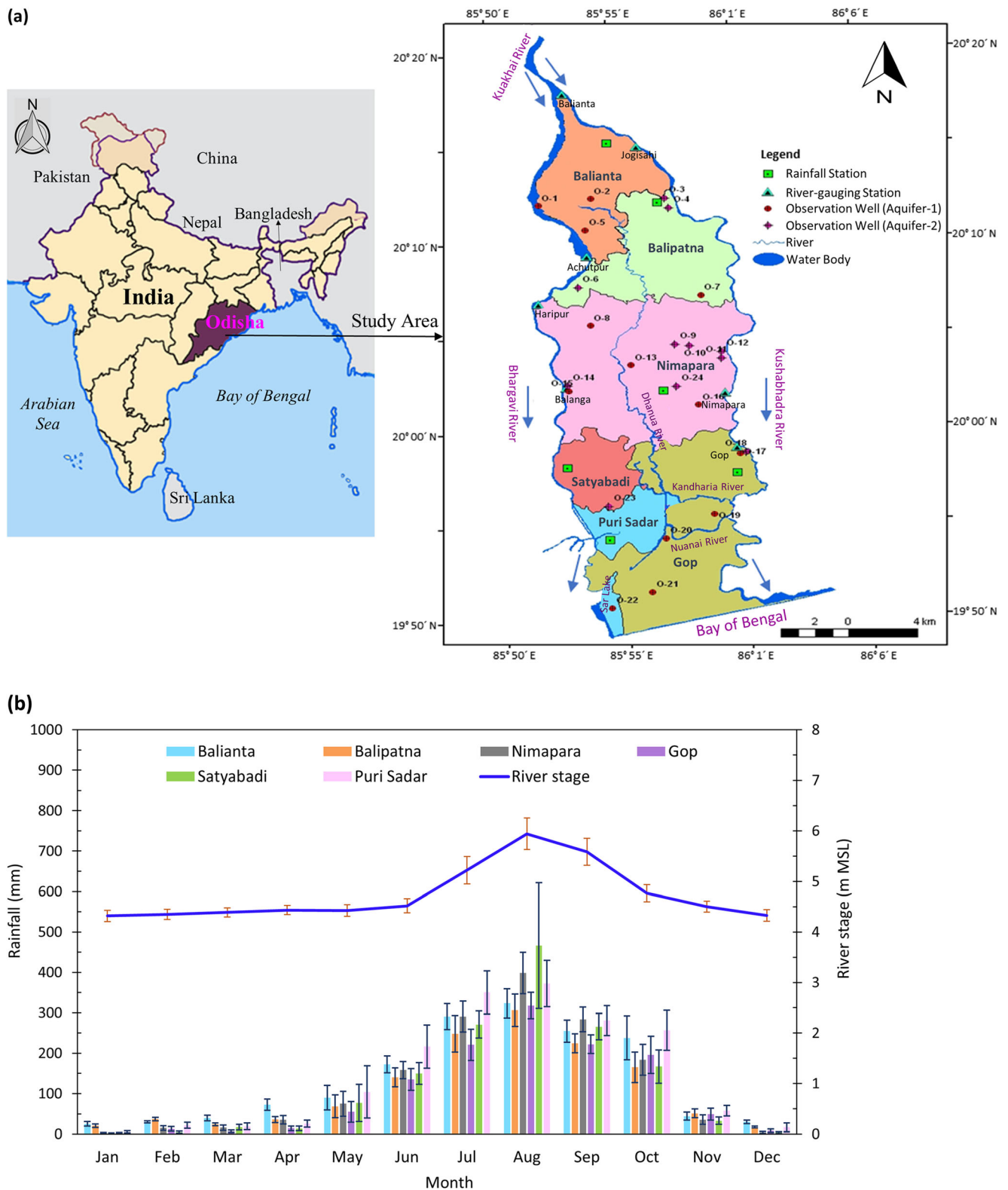


Fig. 1 a Location map of the study area with observation wells, rainfall stations and river gauging stations. *Aquifer-1* refers to the shallow (unconfined) aquifer; *Aquifer-2* refers to the deep (confined) aquifer. b

Mean monthly rainfall at six rainfall stations and river stage at Nimapara gauging station for the 1990–2011 period with standard error bars

Fig. 2 Location of pumping wells and pumping test sites in the study area



hydraulic properties considered in this model are presented in the following subsections.

Hydrogeologic framework

Stratigraphy models or 3D geological models (a series of stacked gridded surfaces) were created using a combination of the Borehole Manager stratigraphy tools and kriging interpolation from the RockWorks15 software package (RockWare 2010). Lithologic data collected from 108 well logs (Fig. 3a) over the Kushabhadra-Bhargavi interbasin were used to create the 3D model. Then, 16 geologic profiles were created by slicing through nine

E–W sections and seven N–S sections, the transects of which are presented in Fig. 3a—for instance, a geologic profile (vertical slice of the modeled lithology) along the N–S D–D’ cross-section is illustrated in Fig. 3b. These cross-sections were then analyzed to determine aquifer layers and confining layers as well as their depth, thickness and areal extent in the basin.

Figure 3c demonstrates a three-layered system of the Kushabhadra-Bhargavi interbasin. The first aquifer layer (aquifer-1) is mostly unconfined and consists of fine sand, medium sand, coarse sand or coarse sand with pebbles—the fine to medium sand being the predominant material (Fig. 3b). The thickness of aquifer-1 varies from 3.4 to 46.5 m over the

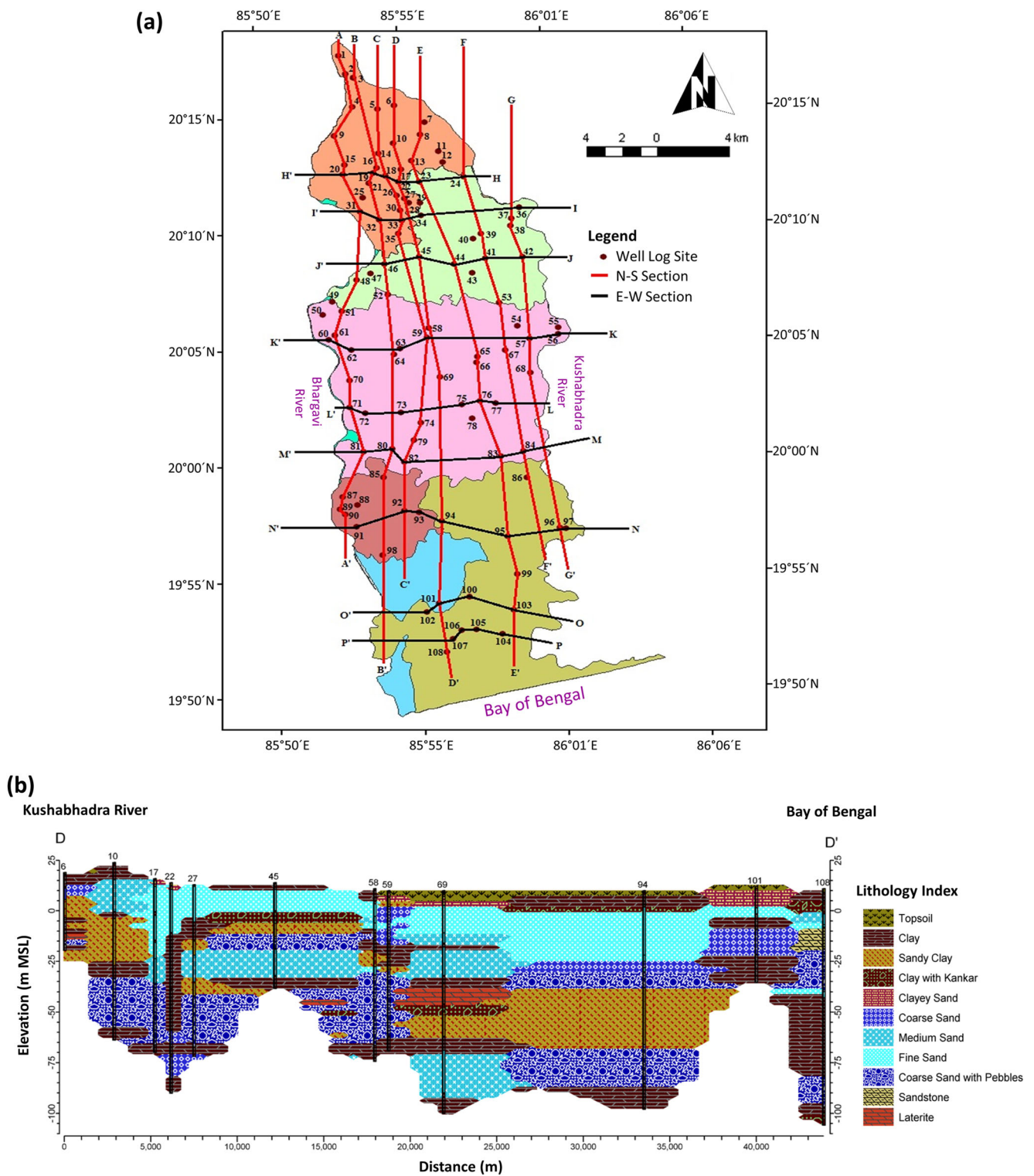


Fig. 3 **a** Locations of 108 well log sites with 16 geologic cross-sections (nine E–W sections, seven N–S sections). **b** Geologic profile of the study area along the N–S D–D' cross-section. **c** Conceptual model of the Kushabhadra–Bhargavi interbasin along the N–S D–D' cross-section

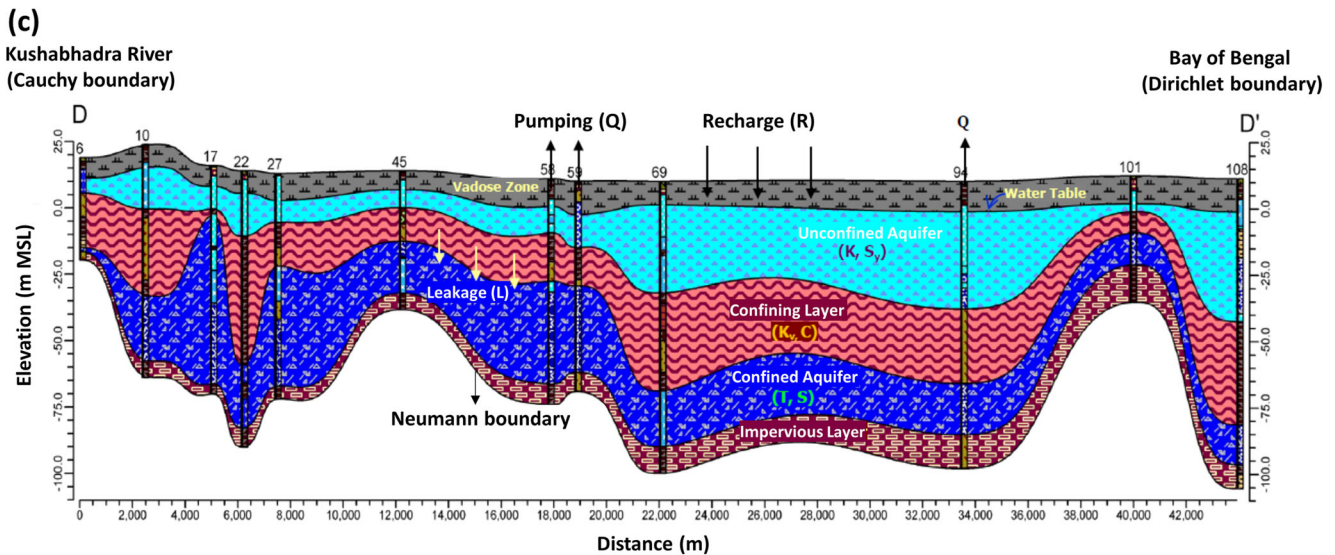


Fig. 3 (continued)

basin with the aquifer depth varying from 1.2 to 62.6 m. Aquifer-1 is underlain by a confining layer which mainly consists of clay/sandy clay with thickness ranging from 2.1 to 60.01 m and depth ranging from 6.5 to 92.8 m. Due to the presence of fine or medium sand within the clay bed at some sites, it is most likely to contribute to leakage into or from the two aquifers depending on the hydraulic condition (Fig. 3b). The second aquifer layer (aquifer-2) is confined between a confining layer at the top and an impervious layer at the bottom (Fig. 3c). This layer is predominantly comprised of medium to coarse sand, coarse sand, coarse sand with pebbles. It is a major source of groundwater in the study area with thickness varying from 3.1 to 80.3 m over the basin. The lower confining layer is comprised of a clay hard formation (i.e. bedrock formation lying deep below the land surface and often acts as an aquifer base in alluvial terrains) with thickness ranging from 0.6 to 48.4 m over the basin (Fig. 3b). It is essentially an impervious (impermeable) layer consisting of the base of the lower confined aquifer in this study.

Hydraulic properties

The purpose of the modeling effort was to assimilate the hydrostratigraphic data and other related factors to derive hydraulic properties of the aquifer system so that they can be used to represent the real aquifer system in a comprehensive manner. Prior to the present study, there were no conceptual model, hydraulic property values, or pumping test data available for this particular region; therefore, hydraulic properties of the Kushabhadrha-Bhargavi interbasin were estimated by pumping test data analysis. Time-drawdown pumping tests were conducted at 15 sites in the study area (Fig. 2) from 5 October to 27

November 2012 (Sahoo 2015). The duration of the interference pumping test (13 sites) was 6 h, in which there were 3 h of pumping and 3 h of recovery. The drawdown and recovery were measured with time in the observation wells located in the vicinity of the pumping wells. At the remaining two pumping-test sites, a single well pumping test was conducted by measuring the water level in the pumping well itself, as no monitoring wells were available near these sites. For analyzing the time-drawdown data of wells tapping confined aquifers (five wells), the Theis method (Theis 1935) was used with the help of Aquifer Test software (WHI 2002). For the wells penetrating more than one aquifer layer (10 wells in this study), a novel approach was adopted to analyze the pumping-test data using the MLU program (Hemker and Maas 1987). MLU is based on an analytical solution involving Stehfest's numerical inversion of the Laplace transform and the Levenberg-Marquardt algorithm for parameter optimization. Using the MLU Windows tool (Hemker and Maas 1987), aquifer properties such as transmissivity, storativity, and vertical resistance were estimated.

Estimation of recharge

The choice of recharge methods depends on multiple factors like spatial and temporal resolution, aquifer characteristics and data availability (Flint et al. 2002; Heppner et al. 2007). In this study, a water balance approach was used to estimate potential groundwater recharge from rainfall using Visual HELP (WHI 1999). It is worth mentioning that in recent years, the HELP model has been widely used for the estimation of recharge and its application in groundwater flow modeling (e.g., Berger 2000; Halford and Mayer 2000; Allen et al. 2003; Risser et al. 2005). Visual HELP takes into account the effect of evapotranspiration, runoff, storage, and vertical infiltration under site-specific soil, land cover, and climatic conditions (Schroeder

et al. 1994). It calculates potential net recharge as a residual of all other water balance components and is expressed as:

$$R = P - ET - R_0 - \Delta S \quad (1)$$

where, R = recharge, P = precipitation, ET = evapotranspiration, R_0 = direct runoff, and ΔS = change in storage. This method was used to compute site-specific groundwater recharge at eight sites for the 2000–2010 period. The input data used by the HELP model were rainfall, temperature, wind speed, relative humidity, solar radiations, soil properties, and land cover. The depth and type of formation of the soil profile at each of the 8 sites were obtained from the detailed stratigraphy analysis. The soil properties of the selected sites in the study area were obtained from the Bulletin of Water Technology Centre for Eastern Region, Bhubaneswar, Odisha (Singh et al. 2002). Runoff was estimated by the SCS (Soil Conservation Service) curve number method and evapotranspiration was calculated from the Penman-Monteith equation. The HELP model was run at a daily time step. The point estimates of recharge yielded by the HELP model were interpolated using geographic information system (GIS)-based geostatistical modeling in order to determine spatial distribution of groundwater recharge over the study area.

Development of the groundwater-flow model: numerical model

The numerical groundwater-flow model of the Kushabhadra-Bhargavi interbasin developed in this study employed 1997–2011 hydraulic head observations and the hydrogeologic framework described in the conceptual model. The numerical model was used for transient simulation of historical conditions and generation of scenarios under different management options, as well as projections for potential future scenarios.

Model domain, grid design and boundary conditions

The study area was discretized into 85 rows and 80 columns using the Grid module of Visual MODFLOW software, which resulted in 6,800 cells, each having a dimension of approximately 304 m × 300 m. The number of rows and columns are the same for all model layers. The hydrogeologic setting of the study area as conceptualized earlier includes three model layers with the upper one being an unconfined aquifer and the lower one being a confined aquifer, separated by a confining unit (i.e., aquitard). The base of the second aquifer (aquifer-2), being an impervious layer, was modeled as a no-flow or Neumann boundary (Fig. 3c). The east and west river-boundaries of the basin were modeled as head-dependent flux or Cauchy boundary condition (using ‘River Package’) and the southern boundary was simulated as constant-head or Dirichlet boundary condition (using ‘Constant Head Package’; Fig. 3c). The input parameters, such as river stage at different time steps, riverbed elevation, riverbed conductivity, riverbed thickness, and the river width at upstream and downstream sites for all the river reaches, were also assigned. Since the deep aquifer (aquifer-2) is not hydraulically connected with the river, the eastern and western boundaries of aquifer-2 were modeled as the no flux boundary (Neumann boundary).

Model parametrization

The model parameters considered in the simulation of the groundwater-flow model comprised of hydraulic conductivity of the aquifer layers, vertical hydraulic conductivity of the confining unit connecting the two aquifers, specific yield of aquifer-1, specific storage of aquifer-2, groundwater abstraction (pumping) and groundwater recharge of the aquifer system. Tables 1 and 2 summarize the aquifer and aquitard

Table 1 Results of pumping-test data analysis for the wells tapping two aquifers

Site	Unconfined aquifer (aquifer-1)		Aquitard		Confined aquifer (aquifer-2)	
	K_h (m/day)	S_y	K_v (m/day)	C (day)	T (m ² /day)	S
Bodhakhandi	4.0	0.15	0.101	402	698	1.1×10^{-6}
Bagalpur	4.8	0.11	0.005	1,347	519	7.8×10^{-4}
Bhadisa	5.0	0.07	0.012	1,725	904	1.3×10^{-4}
Dahijanga-I	11.7	0.02	0.007	2,425	1,267	1.2×10^{-4}
Gadabhingura	4.0	0.03	0.022	987	791	8.1×10^{-4}
Badasrubila	4.8	0.03	0.018	2,451	2,310	4.2×10^{-4}
Baliasasan-II	6.6	0.18	0.009	2,087	1,498	2.1×10^{-6}
Niagarada	3.9	0.09	0.006	1,961	863	1.6×10^{-4}
Chitra-II	13.2	0.21	0.007	2,213	1,045	3.2×10^{-6}
Solapur	7.0	0.19	0.039	495	1,171	9.9×10^{-4}

Note: K_h horizontal hydraulic conductivity in the aquifer, S_y specific yield, K_v vertical hydraulic conductivity in the aquitard, C hydraulic resistance, T transmissivity, and S storage coefficient

Table 2 Results of pumping-tests data analysis for the wells tapping the confined aquifer

Site	Confined aquifer parameters	
	T (m ² /day)	S
Kuanrapur	1,633	8.8×10^{-6}
Ketakiapatna ^a	1,816	–
Munida	471	9.8×10^{-4}
Bentapur ^a	1,265	–
Sundara	971	4.9×10^{-4}

^a Single well test was conducted, T transmissivity, S storage coefficient

hydraulic conductivities (K_h and K_v), specific storage (S_s) and specific yield (S_y) values obtained from the pumping-test data analysis (Hemker and Maas 1987; Theis 1935) at 15 sites, 10 from multi-aquifers and 5 from the confined aquifer. Hydraulic conductivity of the unconfined aquifer varies from 3.9 m/day (site Niangarada) to 13.2 m/day (site Chitra-II) and specific yield of the unconfined aquifer ranges from 0.02 (site Dahijanga-I) to 0.21 (site Chitra-II) over the basin. Based on the hydraulic conductivity values, the unconfined aquifer of the Kushabhadra-Bhargavi interbasin can be characterized as having ‘moderate’ to ‘high’ hydraulic conductivity (Todd 1980). A quasi-3D model was considered in this study; the aquifer layers involve 3D flow (hydraulic conductivities: K_x , K_y , K_z), while the confining layer (aquitard) involves just the vertical flow (vertical hydraulic conductivity: K_v). For all the

zones, a ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity in the aquifer layer (K_x/K_z) was assumed to be 10 to account for aquifer anisotropy (WHI 2006).

Moreover, the vertical hydraulic conductivity of the aquitard (K_v) varies from 0.005 m/day (site Bagalpur) to 0.101 m/day (site Bodhakhandi), while its hydraulic resistance (C) ranges between 402 days (site Bodhakhandi) and 2,451 days (site Badasrubila; Table 1). Transmissivity (T) of the confined aquifer varies from 471 m²/day (site Munida) to 2,310 m²/day (site Badasrubila), which suggests a large spatial variation of transmissivity over the basin (i.e., high heterogeneity of the aquifer system). The values of the storage coefficient (S) of the confined aquifer range from 1.1×10^{-6} (site Bodhakhandi) to 9.9×10^{-4} (site Solapur), which also indicate a significant variation of storage coefficient over the basin. These findings are reasonable as the hydraulic properties of alluvial formations can change within short distances (Anderson and Woessner 1992). It should be noted that the storage coefficient could not be obtained at sites Ketakiapatna and Bentapur because of the single-well pumping tests conducted at these two sites.

These aquifer properties were then subjected to spatial interpolation to assign them to the entire model domain and were used to define several zones. Visual MODFLOW has a built-in module to import and interpolate model property values from discrete data points. The hydraulic properties from pumping test data analysis were imported, interpolated using the ordinary kriging technique with exponential semivariogram, and then used to classify six specific model domain zones, each for the

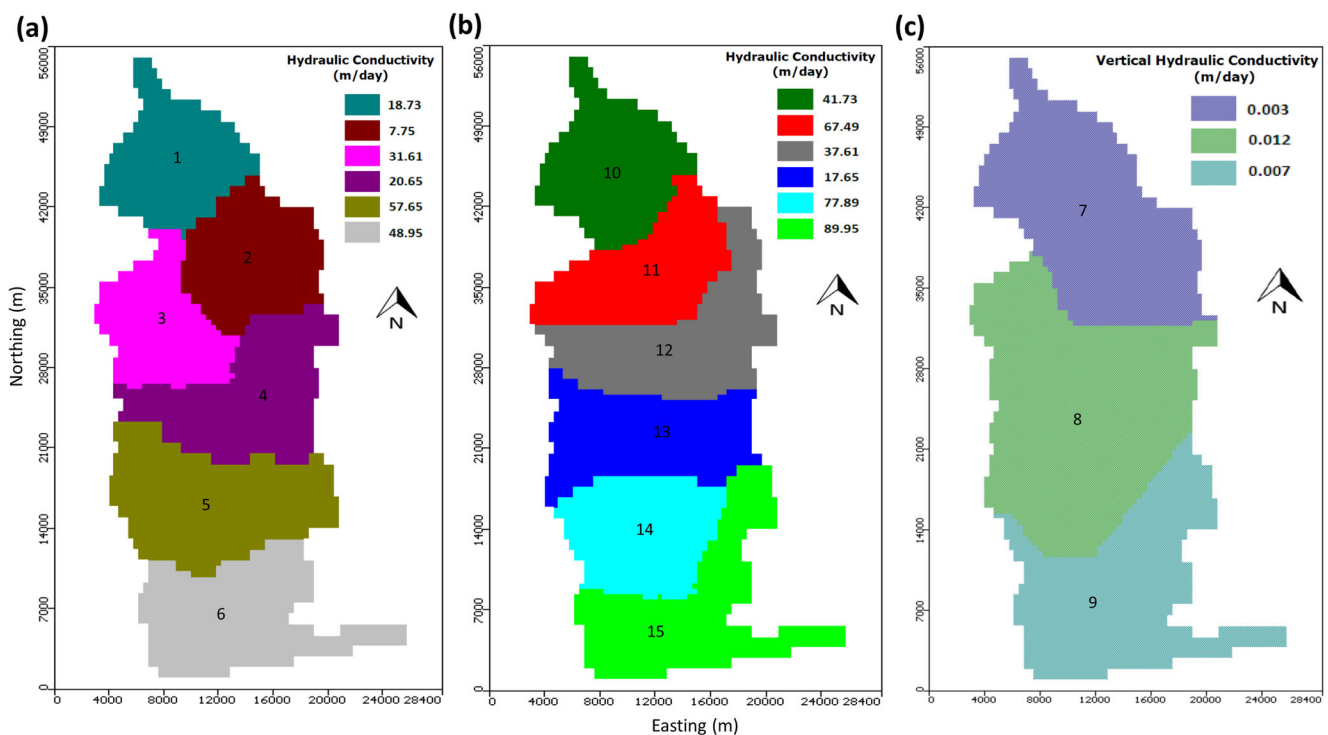


Fig. 4 Hydraulic conductivity zones in the study area for the **a** unconfined aquifer, **b** confined aquifer and **c** aquitard. Numbers indicate corresponding zones for aquifer properties as described in Table 3

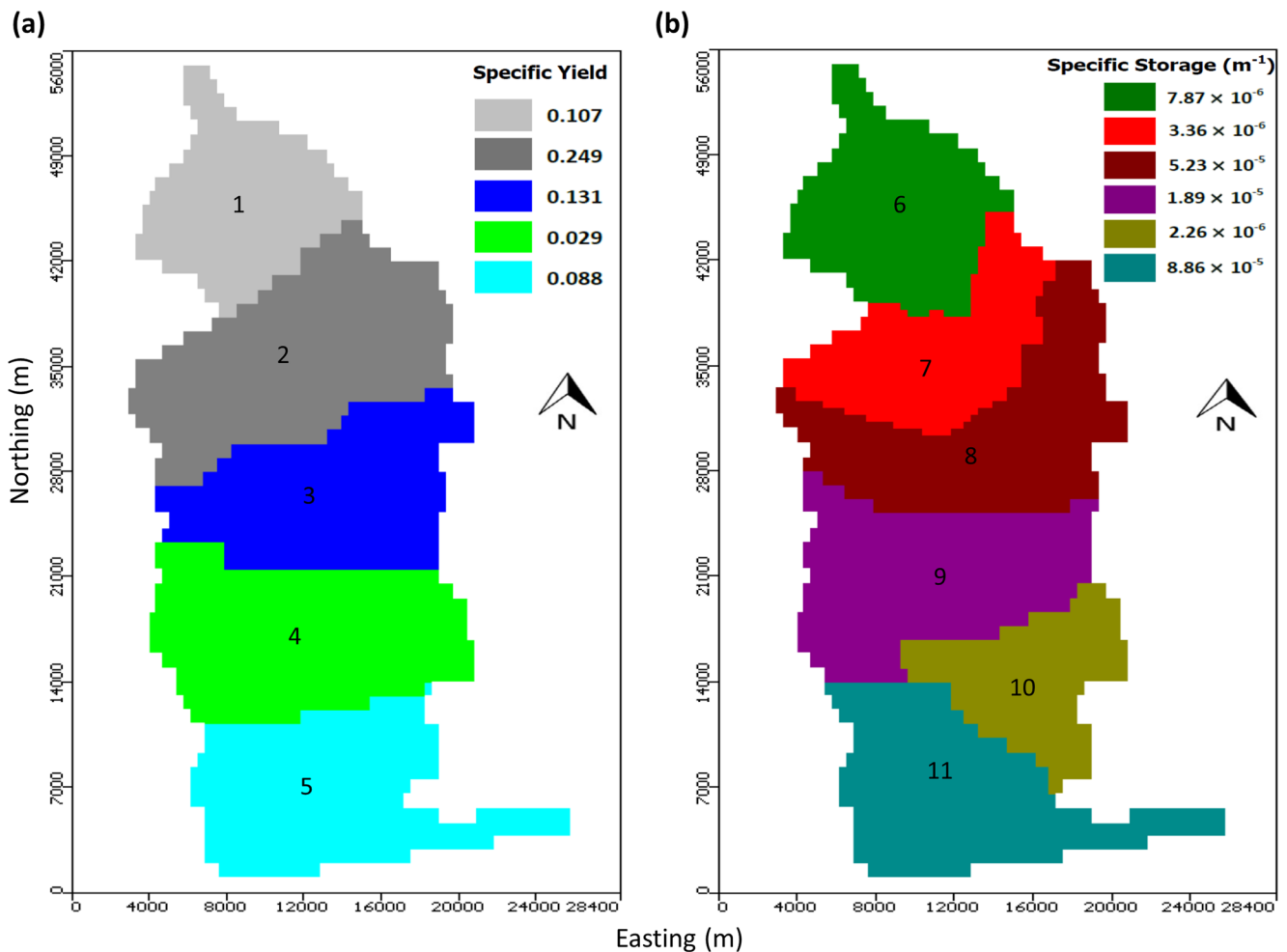


Fig. 5 Zones of **a** specific yield of the unconfined aquifer and **b** specific storage of the confined aquifer. *Numbers* indicate zone number for corresponding aquifer properties as mentioned in Table 3

unconfined and confined aquifers (Fig. 4a,b). The hydraulic conductivity of the unconfined aquifer varies from 7.75 to 57.65 m/day, whereas that of the confined aquifer varies from 17.65 to 89.95 m/day over the basin. Similarly, the vertical hydraulic conductivity values of the aquitard were used to classify three zones as presented in Fig. 4c. Further, spatial variations in the specific yield values of the unconfined aquifer and specific storage values of the confined aquifer were used to define five and six zones, respectively (Fig. 5a,b). Specific yield of the unconfined aquifer varies from 0.029 to 0.249, whereas the specific storage of confined aquifer ranges from 2.26×10^{-6} to $8.86 \times 10^{-5} \text{ m}^{-1}$.

Groundwater abstraction

The Well Package of MODFLOW software is designed to simulate inflows and outflows through recharge and pumping locations, respectively. As mentioned earlier, 77 pumping wells (Fig. 2) are currently in operation in the study area, of which 27 wells are tapping aquifer-1, 37 wells are tapping aquifer-2 and the remaining 13 wells are tapping both aquifer-1 and aquifer-2.

The pumping schedules of these pumping wells were acquired from the OLIC, Bhubaneswar, Odisha, as well as through interaction with the well owners. The pumping rates, locations of pumping wells, and the extent of well screens were input to the multi-aquifer groundwater-flow model.

Groundwater recharge

The Recharge Package of Visual MODFLOW was designed to simulate spatially distributed recharge to a groundwater system. The monthly recharge, as estimated by the water-balance approach of Visual HELP, was input to the groundwater-flow model at the uppermost aquifer (i.e., unconfined aquifer). Rainfall recharge through outcrop of the confined aquifer was not considered in this study because the location of the outcrop is not known; however, the recharge from the unconfined aquifer to the confined aquifer through leakage has been considered. The recharge values were used to set the initial range of recharge across different zones of the model domain. As recharge is sensitive to a variety of factors and typically

uncertain, given the complexity associated with the process, it is also calibrated along with other hydraulic properties.

Calibration and validation of the groundwater-flow model

Calibration of the groundwater-flow model of the Kushabhadrabargavi basin was accomplished by the combined use of the Automated Parameter Estimation (PEST) program and by trial and error techniques. Initially, the aquifer properties were adjusted within their practical ranges using a trial and error method to achieve a somewhat lower level of calibration. Thereafter, model calibration was done using the PEST program incorporated in MODFLOW to obtain a reasonable match (i.e., to minimize the error) between observed and model-simulated hydraulic heads. Water levels of 24 observation wells (13 shallow wells and 11 deep wells) were used to calibrate the 1997–2006 simulation following the standard procedures (Anderson and Woessner 1992; Zheng and Bennett 2002; Bear and Cheng 2010). Although the number of observation wells available for calibration is quite small for such a large model, the wells are dispersed throughout the model domain and thus they are representative of the aquifer conditions. In this study, two-stage calibration followed; firstly, the model was calibrated for the steady-state simulation of groundwater flow, and then the results of the steady-state calibration were used as initial conditions for the transient calibration. The calibration targets for the steady-state model were the hydraulic heads from August 1997 in 24 wells. During transient calibration (1997–2006), the model parameters (hydraulic conductivity of the two aquifers, vertical hydraulic conductivity of the aquitard, specific storage of the confined aquifer, and specific yield and recharge of the unconfined aquifer) were adjusted within their reasonable ranges. The upper and lower bounds of the aquifer hydraulic properties were determined based on the general ranges of the parameters given in Todd (1980). Then, model validation was performed using independent sets of observed hydraulic heads from 2007 to 2011.

Performance evaluation and sensitivity analysis

The performance of the developed multi-aquifer groundwater flow model was thoroughly evaluated by using a set of seven statistical indicators: bias, mean absolute error (MAE), standard error of estimate (SEE), root mean squared error (RMSE), correlation coefficient (R), Nash-Sutcliffe efficiency (NSE) and normalized RMSE (NRMSE). Graphical plots were prepared for both calibration and validation periods, which provided a better picture of the effectiveness of the numerical model in simulating hydraulic heads.

Sensitivity analysis is an essential step in the modeling protocol which helps to understand the degree of influence of various model parameters on the aquifer system and to identify the most sensitive parameter(s), which will need special attention in future studies (Anderson and Woessner 1992). In the

present study, the sensitivity of the model to the estimated parameter values was assessed by calculating the relative composite sensitivity (Doherty 2001) with the help of the PEST module of Visual MODFLOW. The relative sensitivity helps in comparing the effects when the parameters are of different type and possibly of very different magnitudes (Doherty 1994), and was estimated by multiplying its composite sensitivity by the magnitude of the input parameter (Hill 1998). The composite sensitivity (CS) is mathematically expressed as (Hill 1998; Doherty 1994; Anderman et al. 1996):

$$CS = \left[\frac{\sum_{i=1}^N \left(\frac{\partial y_i}{\partial b_j} b_j w^{1/2} \right)^2}{N} \right]^{1/2} \quad (2)$$

where, y_i = simulated head associated with the i th observation, b_j = j th estimated parameter, w = weight of observation, $\frac{\partial y_i}{\partial b_j}$ = sensitivity of the simulated value associated with the i th observation with respect to the j th parameter, and N = total number of observations used in the simulation. This approach was employed for all the input parameters (15 for the unconfined aquifer, 3 for the confining layer and 12 for the confined aquifer) of the groundwater-flow model and high- and low-sensitivity parameters were identified.

Simulation of salient management strategies

Predictive simulations were performed to study the response of the aquifer to hypothetical pumping stresses and recharge conditions as well as to explore future groundwater dynamics under existing pumping and recharge conditions. Thus, four management scenarios were simulated using the calibrated and validated groundwater-flow model of the study area as presented below.

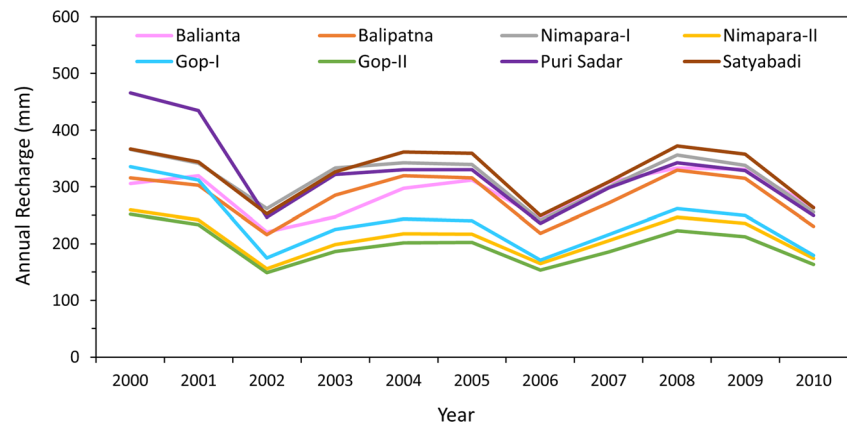
Scenario 1: unconfined aquifer response to various pumping levels

This scenario explores the response of the unconfined aquifer to $\pm 25\%$ and $\pm 50\%$ change in the current pumping level. Thus, it is expected to provide an insight into the upper limit of groundwater extraction from the unconfined aquifer for existing pumping wells.

Scenario 2: confined aquifer response to various pumping levels

This scenario explores the response of the confined aquifer to $\pm 25\%$ and $\pm 50\%$ change in the current pumping level. It is expected to provide an insight into the upper limit of groundwater extraction from the confined aquifer for existing pumping wells.

Fig. 6 Annual variation of recharge estimated by Visual HELP model at eight sites



Scenario 3: unconfined aquifer response to various recharge rates

In this prediction scenario, the response of the unconfined aquifer to 25% increase and 25% reduction, and to 50% increase and 50% reduction in the recharge rate was examined.

Scenario 4: future projection of unconfined and confined aquifer hydraulic heads

This scenario is meant to answer to the question “what will be groundwater condition in the basin after 20 years if the existing conditions of abstraction and recharge continue?”

Results and discussion

Spatio-temporal variations of groundwater recharge

The annual variation of recharge estimated by the Visual HELP model at eight sites for the 11-year period (2000–2010) is illustrated in Fig. 6. Clearly, the maximum amount of annual recharge (> 400 mm) occurs at Puri Sadar in the years 2000 and 2001, while Gop-II receives the lowest amount of recharge for all the years under consideration (2000–2010). It is apparent from Fig. 6 that groundwater recharge varies considerably from one site to another as well as from year to year. The mean annual recharge varies from about 14 to 23% of the mean annual rainfall at different sites. The Recharge Package of MODFLOW was employed to estimate spatially distributed recharge to the groundwater system using ordinary kriging (exponential semivariogram model). The estimates of potential recharge across the model area ranges from 268 to 349 mm/year; these values were used for the first aquifer layer of the model as a starting point during the calibration of the model.

Table 3 Calibrated model parameters of the three-layered groundwater-flow model

Calibrated parameters	Layer	Zone	Calibrated values
K_h (m/day)	Unconfined aquifer	Zone 1	21.0
		Zone 2	8.3
		Zone 3	30.0
		Zone 4	23.5
		Zone 5	48.6
		Zone 6	45.0
K_v (m/day)	Confining layer	Zone 7	0.006
		Zone 8	0.003
		Zone 9	0.008
* K_h (m/day)	Confined aquifer	Zone 10	40.2 (886)
		Zone 11	60.0 (1,732)
		Zone 12	30.0 (1,041)
		Zone 13	13.0 (671)
		Zone 14	65.0 (1,613)
		Zone 15	85.0 (2,170)
S_y	Unconfined aquifer	Zone 1	0.12
		Zone 2	0.23
		Zone 3	0.14
		Zone 4	0.03
		Zone 5	0.08
S_s (m ⁻¹)	Confined aquifer	Zone 6	6.77×10^{-6}
		Zone 7	4.6×10^{-6}
		Zone 8	6.13×10^{-5}
		Zone 9	3.3×10^{-5}
		Zone 10	1.46×10^{-6}
Recharge (mm/year)	Unconfined aquifer	Zone 1	213.7
		Zone 2	259.2
		Zone 3	333.7
		Zone 4	310.4

Note: K_h horizontal hydraulic conductivity in the aquifer; K_v vertical hydraulic conductivity in the aquitard; S_y specific yield; S_s specific storage; values of * K_h in parentheses are transmissivity values (T , m²/day) for the confined aquifer

Calibrated parameters of the numerical model

Table 3 summarizes the calibrated model parameters from the developed groundwater flow model. The hydraulic conductivity values for the upper unconfined aquifer range from 8.3 to 48.6 m/day, vertical hydraulic conductivity values for the confining unit range from 0.003 to 0.008 m/day and hydraulic conductivity values for the confined aquifer range from 13 to 85 m/day. The calibrated specific storage for the confined aquifer is in the range of 1.46×10^{-6} to 7.76×10^{-4} and the specific yield for the unconfined aquifer is in the range of 0.03 to 0.23. Further, the estimated recharge values range from 213.7 to 333.7 mm/year. It is also observed from Table 3 that the model’s calibrated aquifer properties fall within the ranges of interpolated aquifer properties. The discrepancy between the estimated hydraulic conductivity and raw pumping test values in both of the aquifers can be attributed to the differences in riverbed conductance and uncertainty in model calibration as well as interpolation.

Model performance assessment

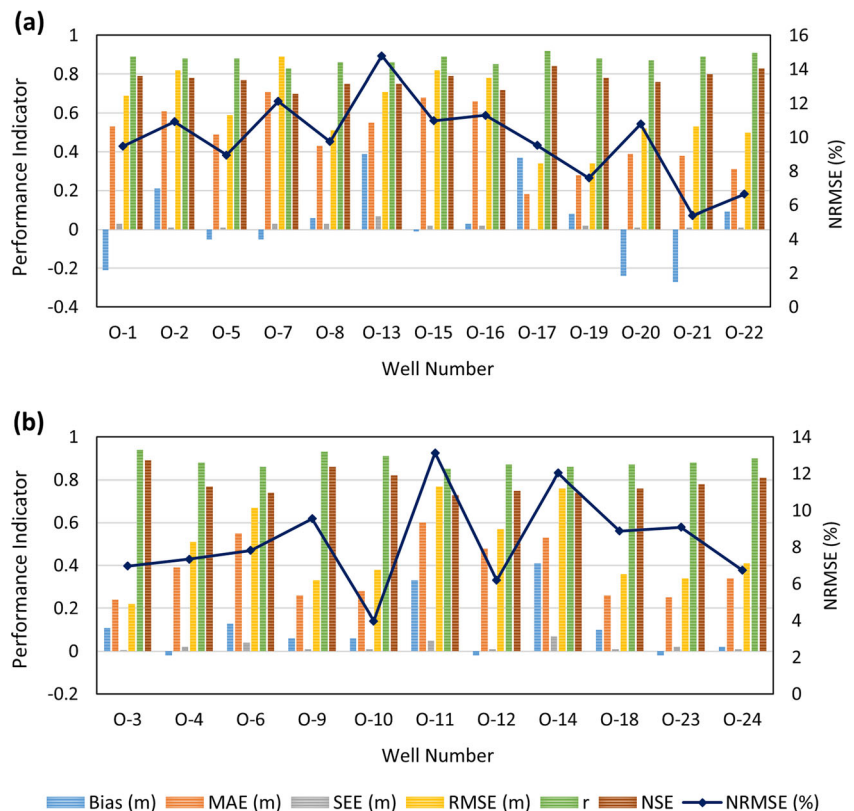
Figure 7a,b indicates the performance statistics of bias, MAE, SEE, RMSE, R, NSE, and NRMSE at 13 sites of the unconfined aquifer and 11 sites of the confined aquifer during validation of the groundwater flow model. It is evident from Fig. 7a,b that for both the aquifers, most of the sites (seven

shallow wells and eight deep wells) have positive bias indicating over-prediction of hydraulic heads by the model during validation. The bias is negative at sites O-1, O-5, O-7, O-15, O-20 and O-21 of the unconfined aquifer and sites O-4, O-12 and O-23 of the confined aquifer, which indicates under-simulation of hydraulic heads at these sites.

Further, at sites O-17, O-22, and O-21 of the unconfined aquifer, the accuracy of simulated hydraulic heads seems to be reasonable as reflected from MAE, SEE, RMSE, R and NSE statistics, whereas relatively inferior simulation is observed at sites O-7 and O-16. On the other hand, in the confined aquifer, sites O-3 and O-9 have the highest accuracy in groundwater-flow simulation in terms of MAE, SEE, RMSE, R and NSE, whereas sites O-11, O-6 and O-14 have the lowest accuracy. However, overall performance of the model in simulating hydraulic heads is reasonable and within acceptable limits for both the aquifers.

In addition, the model fit was examined graphically by plotting the simulated and observed head using the pooled data of hydraulic heads (for each well as well as in each time step) at 13 shallow wells (Fig. 8a) and 11 deep wells (Fig. 8b). The correlation coefficient ranged from 0.89 (unconfined aquifer) to 0.87 (confined aquifer) indicating a good correlation between simulated and observed hydraulic heads. The performance statistics, i.e., R^2 (0.80), RMSE (0.82), MAE (0.58) and NRMSE (8.1%) of model layer-1 (unconfined aquifer) and the R^2 (0.76), RMSE (0.63), MAE (0.51),

Fig. 7 Model performance statistics of the **a** unconfined aquifer and **b** confined aquifer during the validation period, 2007–2011



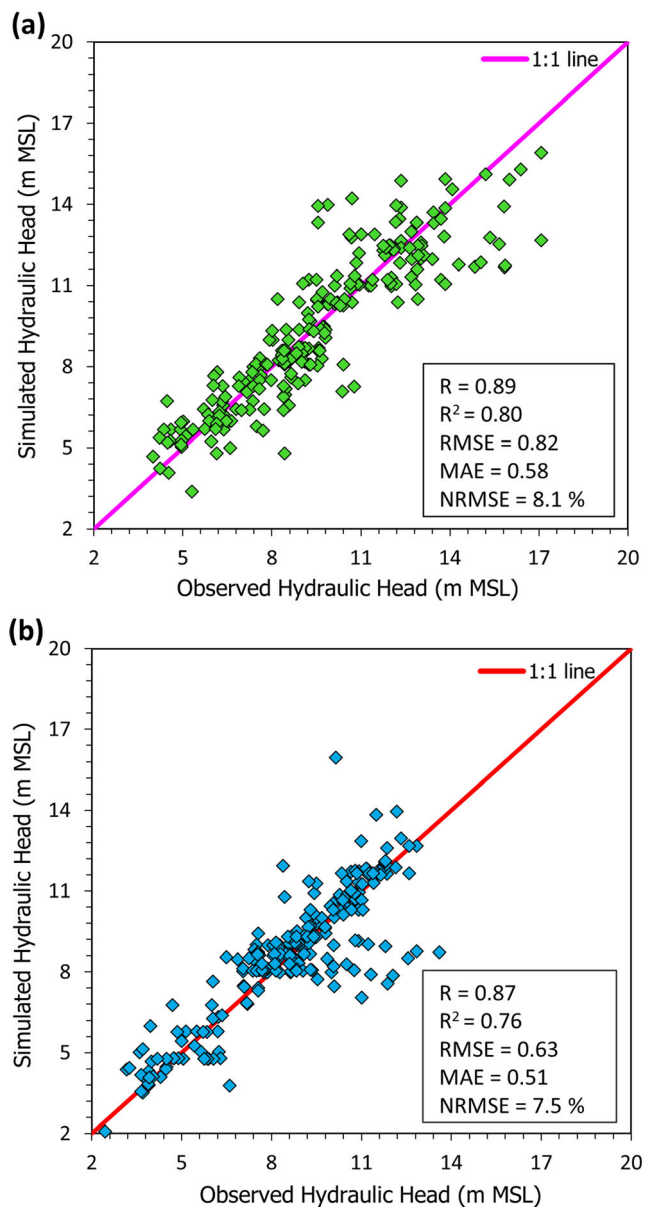


Fig. 8 Relation between simulated and observed hydraulic heads of the **a** unconfined aquifer and **b** confined aquifer during validation

NRMSE (7.5%) of model layer-2 (confined aquifer) suggests very good agreement between observed and simulated hydraulic heads as well as satisfactory validation of the groundwater-flow model for both the aquifers. However, the validation results of the unconfined aquifer are superior to those of the confined aquifer. Simulated and observed hydrographs of selected wells of the unconfined aquifer (sites O-1, O-16 and O-22) and those of the confined aquifer (sites O-4, O-11, and O-18) during the validation period are depicted in Fig. 9a,b, respectively. It is apparent from the figures that the overall patterns of the hydraulic heads are well captured by the simulation model for all the sites, thus validating the effectiveness of the model in hydraulic head prediction.

Simulated groundwater flow dynamics

Pre-monsoon season scenario

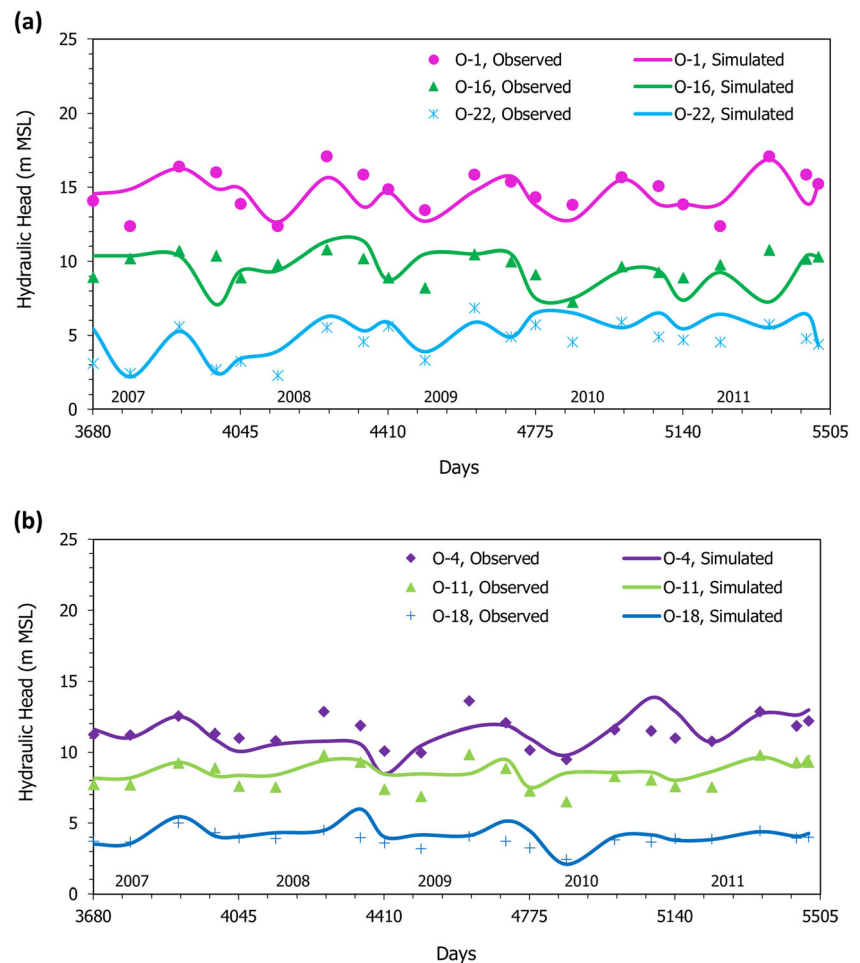
Simulated hydraulic head contour maps of the study area for the representative pre-monsoon season (May 2011) are shown in Fig. 10a,b for the unconfined aquifer and the confined aquifer, respectively. Groundwater flow in the unconfined aquifer is from north to east in the upstream (northern) portion of the study area, while it is also from north to south in the downstream (southern) portion of the study area but with a non-uniform flow pattern over the whole basin (Fig. 10a). In the downstream and central portions of the study area (unconfined aquifer), dense equipotential lines suggest high values of hydraulic gradient, while wider spacing between two consecutive contours indicates lower hydraulic gradient. Further, close perusal of Fig. 10a reveals that the velocity of groundwater is higher in the upstream (northern) portion of the basin, which is represented by larger size of arrows and closer spacing between hydraulic head contour lines. Higher groundwater velocity exists because of the higher values of hydraulic gradient in the upstream (northern) portion of the study area. However, in the downstream-central portion of the study area, there is lower velocity of groundwater, represented by the smaller size of arrows and a wider spacing between hydraulic head contour lines. Lower groundwater velocity can be attributed to the lower hydraulic gradient in the downstream-central portion of the study area.

The overall groundwater flow pattern in the confined aquifer during pre-monsoon seasons is smoother and uniform with a flow direction of north to south (Fig. 10b). This is inferred from the sparse equipotential lines (wider spacing between two consecutive contours) in this aquifer layer, which suggest lower values of hydraulic gradient as compared to the upper layer. Moreover, the velocity of groundwater is higher in the downstream (southern) portion of the basin, which is represented by larger sized of arrows and closer spacing between hydraulic head contour lines. Higher groundwater velocity is attributed to the higher values of hydraulic gradient in the downstream (southern) portion of the study area. 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 hydraulic head contour lines.

Post-monsoon season scenario

The distribution of simulated hydraulic heads for the representative post-monsoon season (November 2011) in the unconfined aquifer and the confined aquifer are presented in Fig. 10c,d, respectively. The direction of groundwater flow in the unconfined aquifer is from north to east in the upstream (northern) portion of the study area and from north to south in the downstream (southern) portion of the study area. Simulated flow routes indicate that groundwater flows more

Fig. 9 Comparison between observed and simulated hydraulic heads for six wells (arbitrarily chosen) in the **a** unconfined aquifer and **b** confined aquifer during validation



slowly through the middle portion of the basin (represented by smaller size of arrows and wider spacing between hydraulic head contour lines) where hydraulic conductivity of the aquifer is smaller. In contrast, groundwater flows faster through the downstream portions of the study area (as indicated by larger size of arrows and closer spacing between hydraulic head contour lines) where hydraulic conductivity of the aquifer is comparatively higher (Fig. 10c). It is also discernible that, due to recharge from rainfall and the rivers during post-monsoon seasons, there is an overall increase in hydraulic heads over the study area. The hydraulic head contour map of the post-monsoon season in the confined aquifer reveals that the flow of groundwater is mostly downward, with an overall flow direction of north to south. The velocity of groundwater in the confined aquifer is higher towards the downstream end of the basin (Fig. 10c).

As far as the temporal variation of hydraulic heads in the unconfined aquifer is concerned, a seasonal variation of 4 m is noticeable in the upstream portion of the basin and of 3 m in the downstream portion (Fig. 10b,c). Further, a comparison of pre- and post-monsoon hydraulic heads in the confined aquifer indicates that there is a seasonal hydraulic head variation of

2.7 m in the upstream portion of the basin and of 0.7 m in the downstream portion of the basin (Fig. 10b,d).

Water balance of the aquifer system

A simulated water budget for the entire aquifer system is calculated using the fluxes in water balance components for all hydrologic features that add or remove water. Table 4 summarizes volumetric inflows and outflows of the groundwater system for the period June 2010 to May 2011 (one water year). The annual recharge from rainfall is 79.06 million cubic meters (Mm^3), and inflow from the river boundary to the aquifer is 7.03 Mm^3 , which makes the total inflow 86.09 Mm^3 . The withdrawal from the aquifer through pumping from wells is the main discharge of the groundwater system and equals 59.13 Mm^3 , and outflow from the aquifer to the river is 1.97 Mm^3 , which makes the total outflow 61.10 Mm^3 . The balance of +24.99 Mm^3 indicates that the aquifer has an increase in groundwater storage during the 2010–2011 period; moreover, the recharge rate is increased substantially (63.78 Mm^3 , 4.2 times the pre-monsoon recharge) during the post-monsoon season. Pumping of groundwater is also

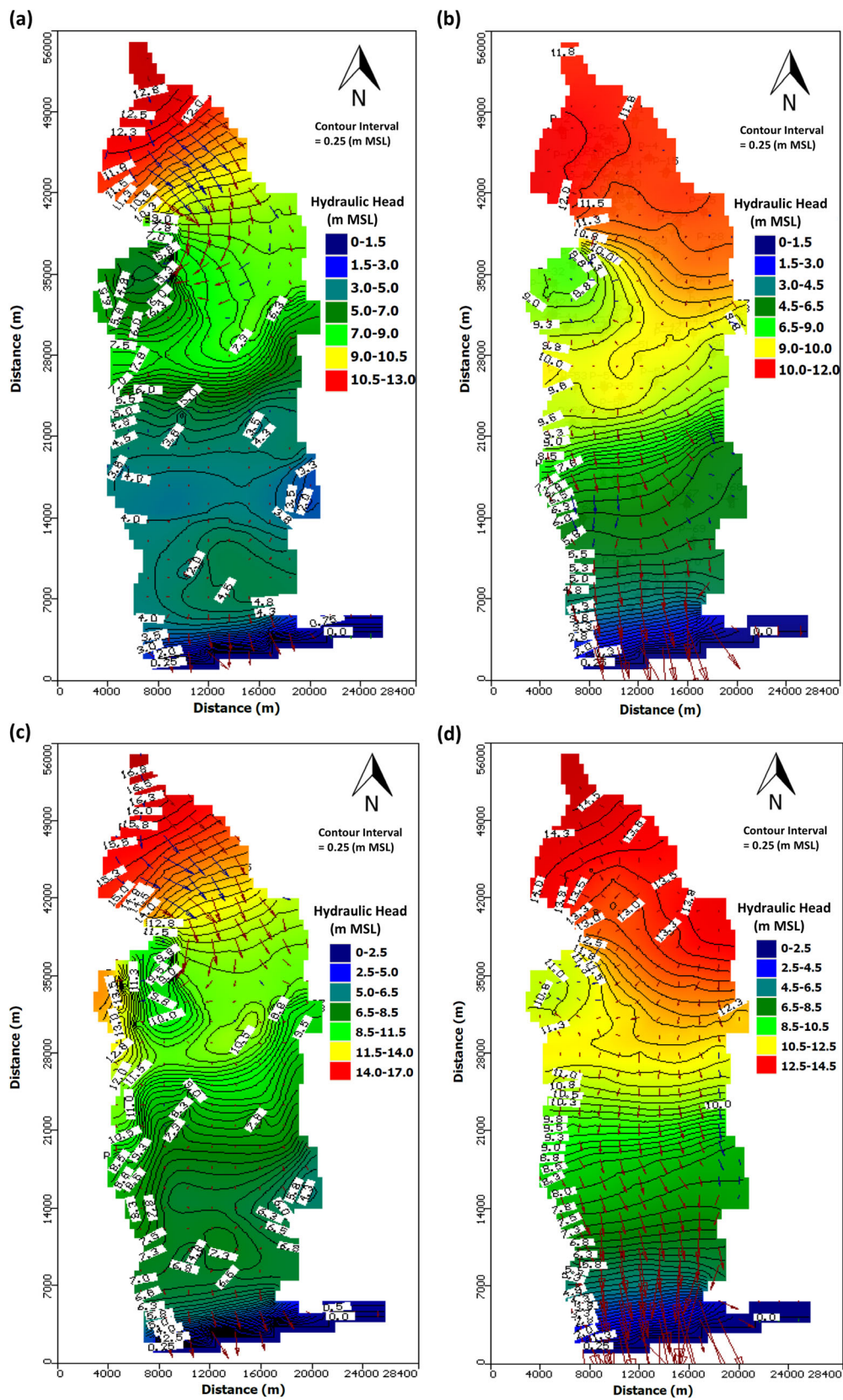


Fig. 10 Pre-monsoon hydraulic head contour maps with groundwater flow vectors for the **a** unconfined aquifer and **b** confined aquifer. Post-monsoon hydraulic head contour maps with groundwater flow vectors for the **c** unconfined aquifer and **d** confined aquifer

Table 4 Groundwater balance in the study area estimated by MODFLOW during 2010–2011

Inflow/outflow components	Total volumetric flow (Mm ³)	Post-monsoon season (Mm ³)	Pre-monsoon season (Mm ³)
River leakage (inflow)	7.03	4.41	2.62
Recharge (inflow)	79.06	63.78	15.28
Total inflow	86.09	68.19	17.9
River leakage (outflow)	1.97	1.12	0.85
Pumping (outflow)	59.13	21.04	38.09
Total outflow	61.1	22.16	38.94
Change in groundwater storage (inflow-outflow)	+24.99	–	–

reduced (21.04 Mm³) during the post-monsoon season, but increases in the pre-monsoon seasons (38.09 Mm³), which matches the actual situation of groundwater utilization in the study area.

River–aquifer interaction

The interaction between surface water and groundwater is also discernible from the mass balance of the aquifer system. In the River Package, two elevations were specified, the elevation of the bottom of the riverbed and the head in the river. When the head in the cell associated with the river drops below the bottom of the riverbed, water enters the aquifer from the river, and when the aquifer head is above the river stage, water leaves the system. A conductance term was multiplied by the difference between the head in the grid and the head in the river to determine the flux. It is found that most inflows (4.41 Mm³) to the aquifer from the Kushabhadra and Bhargavi rivers are during the post-monsoon season. Groundwater discharge to the river occurs through baseflow when the hydraulic head is higher than the river stage, mostly towards the middle and downstream parts of the rivers. Outflows to the rivers from the aquifer during pre-monsoon season are estimated as 0.85 Mm³, which is less than the post-monsoon baseflow (1.12 Mm³). Overall, it indicates that annual rainfall recharge has a significant contribution to the groundwater reserve of the Kushabhadra-Bhargavi interbasin.

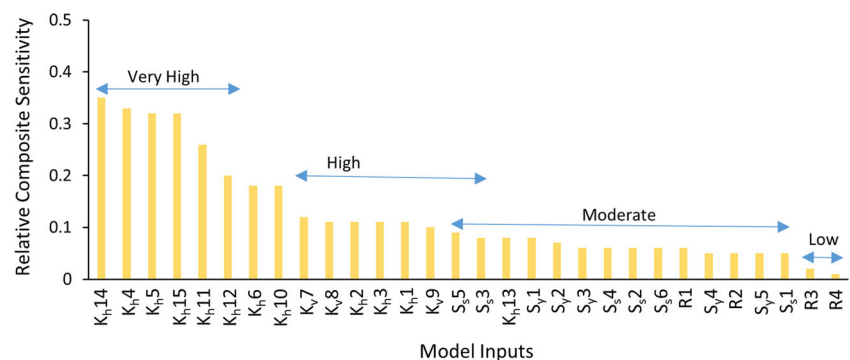
Sensitivity analysis of the model inputs

Input parameters for the developed groundwater-flow model were evaluated for model sensitivity by using relative composite sensitivity (CS_R) statistics as shown in Fig. 11. Sensitivity analysis provides information about the most/least important (sensitive) input parameters in the simulation model (Hill and Tiedeman 2007). It is observed from Fig. 11 that the groundwater-flow model is most sensitive to the hydraulic conductivity of the confined aquifer followed by the hydraulic conductivity of unconfined aquifer, vertical hydraulic conductivity of the confining layer, specific yield of the unconfined aquifer, and specific storage of the confined aquifer. The model is least sensitive to the recharge of the unconfined aquifer (Fig. 11). In this figure, ‘very high’ (CS_R ≥ 0.2) and ‘high’ (0.09 < CS_R < 0.2) sensitivity of the model parameters suggests that even a small error in these parameters will result in a considerable error (uncertainty) in the model outputs. Therefore, these parameters should be estimated with a higher accuracy (precision) in future modeling studies.

Simulation of groundwater management scenarios

Using the calibrated model parameters, simulations were conducted to estimate groundwater responses to changing pumping and recharge conditions as well as to explore future groundwater dynamics under existing pumping and recharge conditions.

Fig. 11 Relative composite sensitivity (CS_R) of the model parameters: *very high* sensitivity (CS_R ≥ 0.2), *high* sensitivity (0.09 < CS_R < 0.2), *moderate* sensitivity (0.05 ≤ CS_R ≤ 0.09), and *low* sensitivity (CS_R < 0.05). The numbers indicate zones of the unconfined aquifer, confined aquifer and confining layer as depicted in Table 3



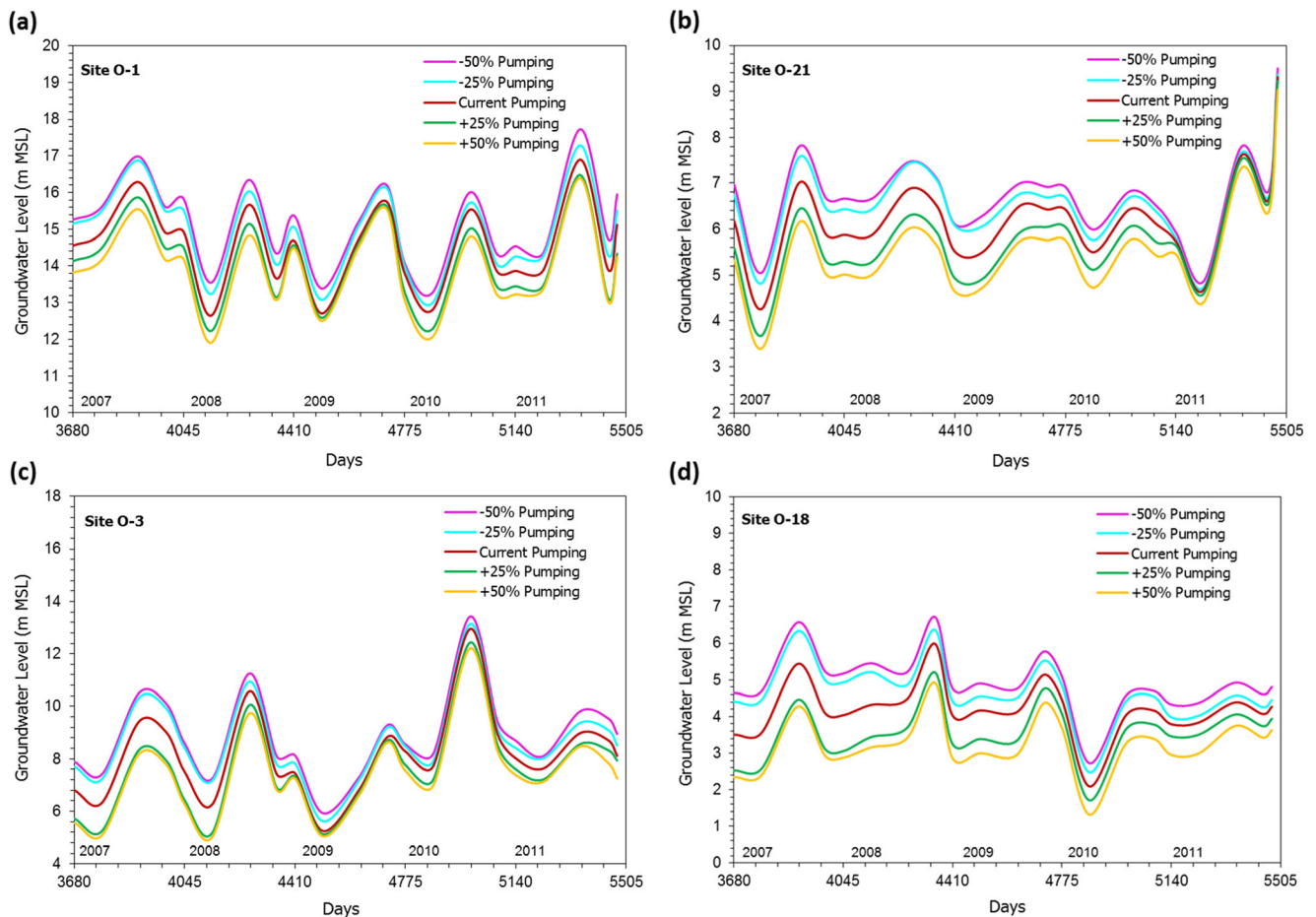


Fig. 12 Hydraulic head scenarios during validation at sites O-1 and O-21 of the unconfined aquifer (a–b) and sites O-3 and O-18 of the confined aquifer (c–d) under decreases (–25%, –50%), and increases (+25%, +50%) in current pumping rate

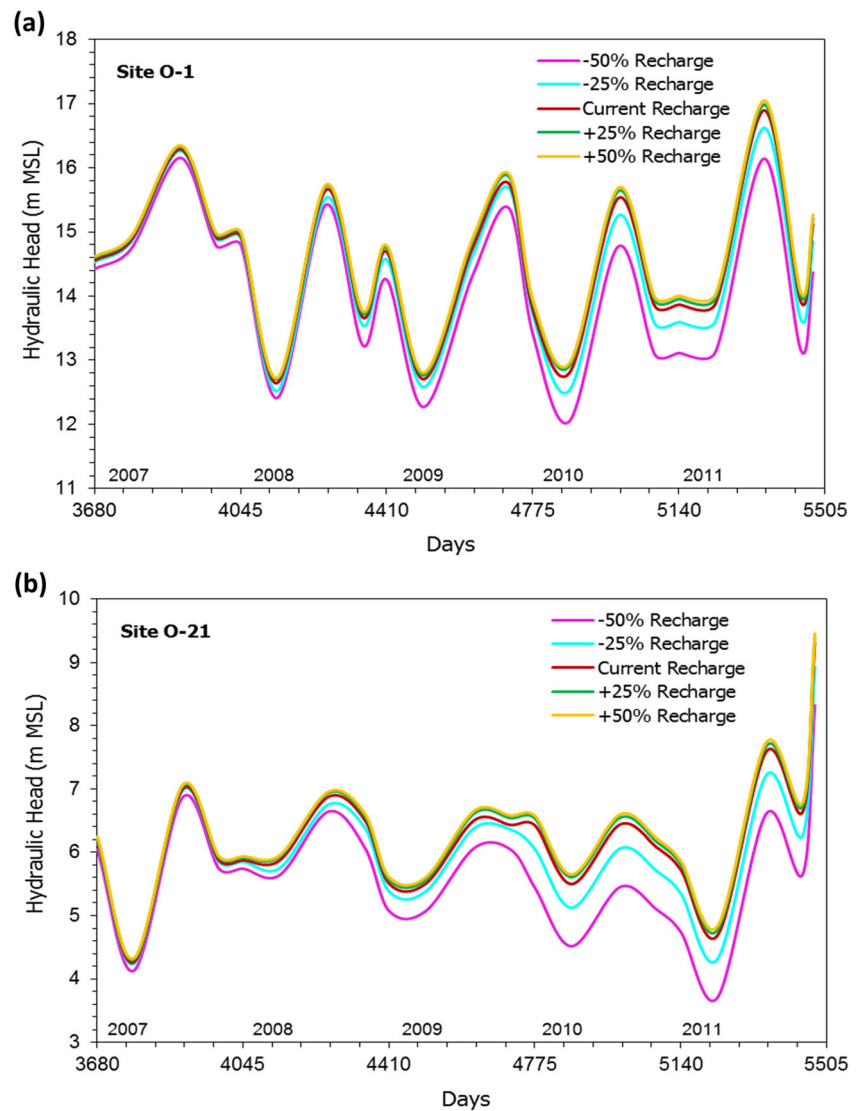
Scenario 1: response of the unconfined aquifer to pumping

The unconfined aquifer was subjected to four levels of pumping, ± 25 and $\pm 50\%$ of the existing pumping rates, and the resulting hydraulic head conditions were analyzed. Figure 12a,b illustrates the responses of two observation wells, O-1 (upstream portion of the basin) and O-21 (downstream portion of the basin), for the validation period (2007–2011). It is evident from these figures that an increase in the pumping rates up to 25 and 50% results in a decrease in the hydraulic head to a maximum of 0.78 and 0.88 m at site O-1, and 0.58 and 0.87 m at site O-21, respectively. Similarly, a decrease in the pumping rates up to 25 and 50% results in an increase in the hydraulic head to a maximum of 0.59 and 0.90 m at site O-1, and 0.56 and 0.79 m at site O-21, respectively (Fig. 12a,b). Thus, an increase or a decrease in the pumping rates up to 25 and 50% results in significant changes in the hydraulic heads at sites O-1 (except 2009–2010 years) and O-21 (except 2011); this trend was also observed for the remaining wells of the unconfined aquifer.

Scenario 2: response of the confined aquifer to pumping

The response of the deep observation wells (confined aquifer) to 25 and 50% increased/decreased pumping condition was estimated. Figure 12c,d shows the simulated hydraulic head hydrograph at two sites, O-3 and O-18, for the validation period. It is apparent from Fig. 12c,d that the increase or decrease in pumping rates up to 25 and 50% results in significant variations in the hydraulic heads at sites O-3 and O-18, and this trend was also pronounced at the remaining sites of the confined aquifer. An increase in pumping rates up to 25 and 50% results in a decrease in the hydraulic head to a maximum of 1.08 and 1.24 m at site O-3, and 0.98 and 1.17 m at site O-18, respectively. Similarly, a decrease in the pumping rates up to 25 and 50% results in an increase in the hydraulic head to a maximum of 0.90 and 1.08 m at site O-3, and 0.90 and 1.14 m at site O-18, respectively (Fig. 12c,d). It is noteworthy that the effect of increase or decrease in the pumping rates is more significant in the confined aquifer than the unconfined aquifer. This is because for the same amount of pumping, drawdown will be less in the unconfined aquifer compared to the drawdown in the confined aquifer because the storage

Fig. 13 Hydraulic head scenarios during validation at sites **a** O-1 and **b** O-21 of the unconfined aquifer under decreases (–25%, –50%), and increases (+25%, +50%) in current recharge conditions



coefficient of the unconfined aquifer is usually much higher than that of the confined aquifer.

Scenario 3: response of the unconfined aquifer to recharge

The hydrologic responses of the unconfined aquifer to increased/decreased recharge and existing pumping condition are presented in Fig. 13a,b. It is apparent from Fig. 13a,b that the hydraulic heads of the unconfined aquifer respond to the increase and decrease in recharge, the trend being similar for the remaining 10 sites of the unconfined aquifer. The effect of increase and decrease in the recharge rate by 50% results in increase and decrease in the hydraulic heads to a maximum (+)0.16 and (–)0.76 m at site O-1, and (+)0.16 and (–)0.98 m at site O-21, respectively. In contrast, the increase in recharge rate by 25% has a very low impact on the hydraulic head, i.e., a maximum increase of 0.11 m at sites O-1, and 0.09 m at site O-21. On the other hand, a decrease in the recharge rate by 25%

results in lowering of the hydraulic head of the unconfined aquifer to a maximum amount of 0.27 m at site O-1, and 0.36 m at site O-21. Thus, a decrease in recharge rate has a more pronounced effect on the hydraulic head than the increase in recharge rate at all the observation wells of the unconfined aquifer.

Scenario 4: long-term groundwater scenario

The model was used to investigate the future (2012–2031) conditions of hydraulic heads in the study area using calibrated input parameters under existing conditions of pumping and recharge. The predicted hydraulic heads at three shallow wells and three deep wells for 2012–2031 period are illustrated in Fig. 14a,b. It is evident from Fig. 14a that although a significant annual variation of hydraulic head is noticeable from 2012 to 2031, the hydraulic head in the unconfined aquifer varies from 8.3 to 15.7 m at site O-2, from 2.8 to 10.8 m at site O-15, and from 2.5 to 8.1 m at site O-21, over the 2012–

2031 period. It is also apparent from Fig. 14a,b that there is a slight decline of hydraulic heads at sites O-2 and O-15 during 2019–2021 and 2029–2031 periods. This may be because of insufficient natural recharge during those years as compared to groundwater withdrawals; therefore, groundwater extraction during these years should be minimal and within optimal pumping rates to curb groundwater depletion. Moreover, the repeating pattern of the hydraulic heads indicates the effects of the wet period (no/least groundwater pumping) and dry period (highest groundwater pumping) in each year.

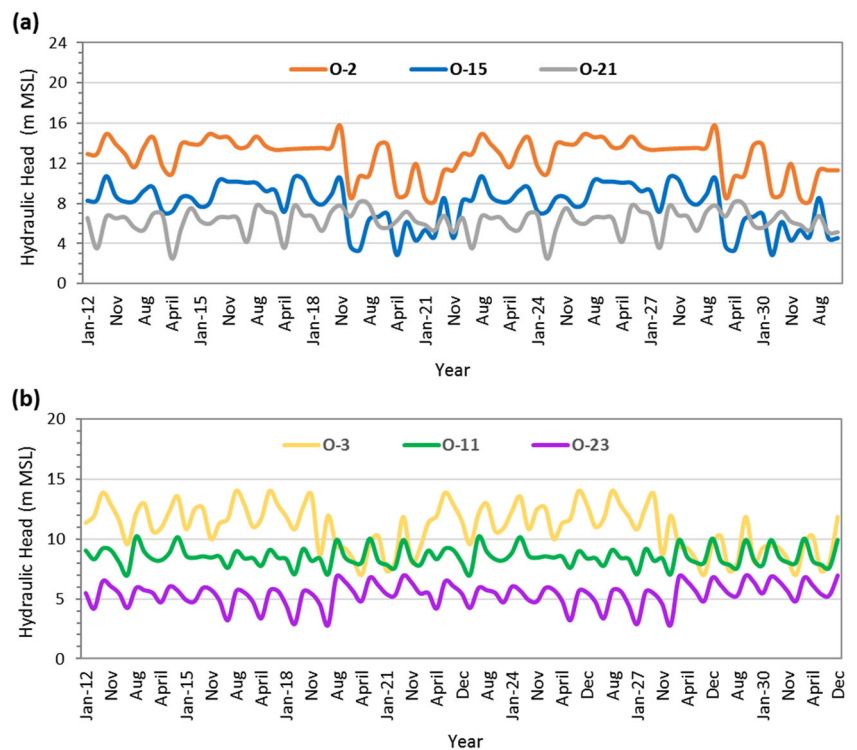
The long-term predictions of hydraulic heads at three selected sites (O-3, O-11 and O-23) of the confined aquifer over 2012–2031 period are illustrated in Fig. 14b. A close perusal of this figure depicts that hydraulic heads from 2012 to 2031 vary significantly with a peak in the month of July–August. Further, maximum and minimum hydraulic head elevation for the prediction period range from 7 to 14 m at site O-3, 7 to 10.2 m at site O-11, and 2.8 to 6.9 m at site O-23. Like the unconfined aquifer, there is a slight declining trend of hydraulic head at site O-3 during 2019–2021 and 2028–2031 periods. This may be because of more withdrawals of groundwater during these periods as compared to rainfall recharge; thus, groundwater should be extracted under a controlled rate during these years to avoid significant depletion of groundwater in the confined aquifer, especially during dry periods. However, water-table rise during post-monsoon seasons sometimes becomes the cause of waterlogging in coastal regions, which is because of excessive recharge due to uncontrolled release of canal waters, canal seepage, return flow of irrigation and poor drainage in the

flat terrain. This emphasizes the need for conjunctive use of surface water and groundwater to enable vertical drainage and to ensure sustainable supply of freshwater in the study area. Given the Bay of Bengal as one boundary of the study area, groundwater withdrawal from the basin should be properly monitored and kept under control in order to avoid seawater intrusion into the freshwater aquifers, particularly in the downstream portion of the study area. At present, these projected simulation results can be considered as a baseline scenario and will be helpful in assessing the influence of future climate change/land use change, when adequate data (climate/land use/withdrawal data) will be available in the future.

Model limitations and future studies

There are a few discrepancies between model-calibrated and pumping-test-estimated hydraulic properties, including discrepancies between model-simulated and original groundwater recharges, and between simulated hydraulic heads and observed hydraulic heads. These uncertainties arise from spatial interpolation of hydraulic properties, assignment of riverbed conductance without calibration, and groundwater pumping data, as well as error in the input observations from measurement. Future studies will investigate these uncertainties thoroughly to improve model predictions. In addition, the developed model will be applied to study the impacts of changing climate/land use/agricultural water uses on groundwater resources as well as detailed interactions between seawater and freshwater using available groundwater quality data. Such studies will help develop efficient

Fig. 14 Simulated future hydraulic heads at **a** sites O-2, O-15, and O-21 of the unconfined aquifer and **b** sites O-3, O-11, and O-23 of the confined aquifer, for 2012–2031 period



management strategies under different climatic/socio-economic scenarios to ensure long-term water security and sustainable groundwater management for protecting vital groundwater resources and preventing environmental degradation in the region.

Conclusions

The present study was carried out in a three-layered groundwater system of the Kushabhadra-Bhargavi interbasin located in the Mahanadi delta of Odisha, with an overall objective to understand the complex aquifer system and groundwater flow dynamics in the study area. A conceptual model of the study area was developed using detailed analysis of hydrologic and hydrogeologic data, and field investigations. Using this conceptual model, a quasi-3D groundwater-flow model was developed to simulate groundwater flow in the three-layered groundwater system. This model was calibrated using automated calibration code PEST and hydraulic head observations of 24 wells from 1997 to 2006, and validated using 2007–2011 observations. Sensitivity analyses of the calibrated and validated model were performed using relative composite-scaled sensitivity, considering all the input parameters of the model. Predictive simulations were performed to examine the response of the aquifer system to different pumping levels and recharge rates under various management options.

The results of stratigraphy analyses indicated that the thickness of unconfined aquifer varies from 3.4 to 46.5 m, whereas that of the confined aquifer varies from 3.1 to 80.3 m over the basin with an interconnecting confining layer of thickness ranging from 2.1 to 60.0 m. The mean rainfall recharge estimated from Visual HELP model shows considerable variation at Puri Sadar followed by Gop-I, Satyabadi, Nimapara-I and Balipatna with a negligible variation of recharge at Balianta, Gop-II and Nimapara-II. The calibrated values of hydraulic conductivity of the unconfined aquifer range from 8.3 to 48.6 m/day, while that of the confined aquifer varies from 13 to 85 m/day. The calibrated values of specific storage range from 1.46×10^{-6} to 7.76×10^{-4} ; specific yield ranges from 0.03 to 0.23 and recharge values range from 213.7 to 333.7 mm/year.

The results of the sensitivity analysis revealed that the model is most sensitive to the hydraulic conductivity of the confined aquifer followed by the hydraulic conductivity of the unconfined aquifer, vertical hydraulic conductivity of the confining layer, specific yield of the unconfined aquifer, specific storage of the confined aquifer and recharge of the unconfined aquifer. The simulation of salient groundwater management scenarios indicated that an increase or a decrease in pumping rates has a significantly higher effect on the confined aquifer as compared to the unconfined aquifer. Future projections of hydraulic heads (2012–2031) indicate that under existing conditions of groundwater abstraction and recharge, there is a slight declining trend of hydraulic head at both shallow and deep aquifers during pre-

monsoon seasons of 2019–2021 and 2029–2031 years. Thus, groundwater should be extracted under controlled rate during these years to avoid significant depletion of groundwater, especially during dry periods. However, water balance of $+24.99 \text{ Mm}^3$ during 2010–2011 indicates that the aquifer has an increase in groundwater storage during this period, which is due to higher total recharge as compared to total discharge from the wells, especially during post-monsoon season. Further, it is observed that the post-monsoon groundwater recharge is 4.2 times that of the pre-monsoon season.

Despite large groundwater potential in the basin, groundwater utilization in the area is disturbed with issues arising from salinity hazards, rising water table in canal commands during post-monsoon seasons, and groundwater contamination due to natural or anthropogenic factors. A considerable area is either under waterlogged condition or prone to waterlogging in the coastal region of the study area adjacent to Bay of Bengal. Excessive recharge due to uncontrolled release of canal waters, canal seepage, return flow of irrigation, and poor drainage in the flat terrain are some of the causes of waterlogging near the coastal region, which emphasizes the need for conjunctive use of surface water and groundwater to enable vertical drainage of excess water to ensure a sustainable supply of freshwater in the study area. For optimal development of groundwater resources, further investigations should be directed towards studying the quality of groundwater, seawater/freshwater interaction and the effects of pumping on seawater intrusion.

Groundwater depletion due to unsustainable groundwater extraction is one of the major global problems. In addition, climate change and population growth in different parts of the globe will place additional stress on already exploited groundwater resources. This kind of regional groundwater modeling study will be useful for exploring groundwater system dynamics and understanding the flow patterns, evaluating responses of the groundwater system to stresses and subsequent groundwater development scenarios. Moreover, the findings from this study provides effective means to estimate important water budget components like recharge, groundwater extraction and aquifer storage, and then quantifying sustainable aquifer yield and predicting the impacts of human activities, including increased groundwater withdrawals and changes in the land use/land cover pattern. The quantitative results can provide insights for planning field data collection and boost decision making among the global hydrogeological community. In addition, the findings can provide better understanding of the current and future water cycle trends and help explore possible ways for suitable management strategies and sustainable adaptation. Future work as a follow-up to this study can be directed towards collecting improved data related to future climate and hydrology, which in turn will be helpful to evaluate the impacts of changes in climate, land use and water demand in the region, as well as benefit the long-term planning and management of water resources. In addition, future studies will thoroughly investigate the

uncertainties arising from the interpolation method, model calibration, and input observations to improve model predictions. The methodology for model development presented here can be directly applied to other basins of India or regions with similar hydrogeologic conditions worldwide, provided sufficient data are available to define the conceptual model. For future groundwater modeling studies, it is recommended that an integrated surface–subsurface model should be developed that can consider all stages of the hydrologic processes, especially in areas where inflow/outflow rates and river–aquifer interactions are highly uncertain owing to highly variable climatic conditions and inconsistent irrigation practices.

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