

## SIMULATING RIVER-AQUIFER DYNAMIC INTERACTION IN THE REGIONAL UNCONFINED AQUIFER OF SOUTHWESTERN BANGLADESH

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### ABSTRACT

*The coastal belt in the southwestern Bangladesh is facing a unique problem compared to other parts of the country because of the direct interaction of the saline surface water (SW) from the coastal rivers and nearby sea with the fresh groundwater (GW) in the underlying aquifers. In this study, an integrated river-aquifer model is developed for the shallow unconfined aquifer in the southwestern Bangladesh to simulate the GW flow characteristics and dynamic flow exchanges between the rivers and aquifer systems. Well-known USGS numerical code for GW flow simulation, MODFLOW and its river simulation package (RIV) are applied in the framework of GW Modeling System (GMS) software, which is satisfactorily calibrated against the observed water levels. Simulation result demonstrates that fluctuations of hydraulic heads are dependent on seasonal variations of recharge from precipitation and riverbed leakage. In addition, the river-aquifer relationships proved to be very responsive to water table fluctuations, which indicate the losing or gaining characteristics of the river reaches. This form of dynamic interactions in an integrated river-aquifer system is important in the field contaminant hydrology, which greatly influence the overall system. The study finally concludes that the developed integrated river-aquifer model opens a window for better understanding of a coupled SW-GW system and thereby finding the potential causes of shallow GW pollution by the contaminated recharge water particularly in the coastal area of southwestern Bangladesh.*

**Keywords:** Conceptual model, Dynamic interaction, GMS, Groundwater flow, MODFLOW, River-aquifer

### 1. INTRODUCTION

Globally freshwater resources are getting scarce in view of ever increasing freshwater demands due to rapid growth of population, uncontrolled urbanization and increased industrial activities. Every year some new regions, which earlier had surplus water, are entering into the domain of water scarce or water stress areas. In the past, efforts were given only on the development of additional sources to meet the rising demand for freshwater resources without considering the quality aspect. However, the most significant aspect of any water resources planning and management strategy is to ensure adequate supply of water with acceptable quality (Nobi and Das Gupta, 1997). Groundwater (GW) is usually the major source of freshwater in the coastal region because of limited potable freshwater supply from surface water (SW) bodies, where saltwater intrusion is a frequent and widespread problem (Werner and Gallagher, 2006). As rapid urbanization and industrial development continues to expand around the world's rivers and coastlines, there is a strong possibility of unintentional releasing contaminants to subsurface and/or SW sources that demands the need for effective assessment of such environments (Winter, 2000). In the past, groundwater and surface water (GW-SW) systems were considered as isolated components of the hydrological system, which led to the development of different approaches to modeling and management of these systems. However, according to the recent developments in hydrological research, GW-SW are reasonably being treated as part of the same system and both systems are found to be interacting in a variety of physiographic and climatic landscapes (Winter, 2001; Hayashi and Rosenberry, 2002; Sophocleous, 2002). It is now widely recognized that both GW-SW systems are inherently linked to each other and several studies have been carried out in the last decades (e.g. Sophocleous and Perkins, 1993; Clement et al., 1996; Swain and Wexler, 1996; Nobi and Das Gupta, 1997; Simpson et al., 2003; Rodriguez et al., 2006; Wahid et al., 2007). Thus, uncontrolled development or contamination of one system obviously affects the other (Sophocleous, 2002). Moreover, the unplanned exploitation of GW sometimes may cause severe environmental consequences (Don et al., 2005). Therefore, river-aquifer interaction is significant in that case, where GW is contaminated by polluted SW (for example salinity intrusion) and in situations where degradation of SW is caused by discharge of saline or other inferior-quality GW from underlying aquifers. Therefore, quantitative understanding of the basic principles of dynamic interactions process for a GW-SW system and its appropriate assessment in an integrated river-aquifer system is essential for the effective management of water resources. In this regard, mathematical modeling technique plays a very significant role.

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In any water resource planning and management, the flow exchange between the underlying aquifers and interconnected rivers is an important consideration. During the investigation of river-aquifer dynamic interaction, the practical obstacle arises from the difference in response times of GW-SW to dynamic variations in the systems. Due to this difference in time response, numerical modeling of stream-aquifer systems has typically been approached either by using a single model or a coupled model (Rodríguez *et al.*, 2006). In case of single model approach, a GW model solves the surface component in a simple way. MODFLOW, a finite difference GW flow model of USGS developed by McDonald and Harbaugh (1988), has been used in many engineering applications whenever the single model approach is sought (e.g. Sophocleous and Perkins, 1993). In the coupled model approach, a GW flow model is coupled internally or externally to a SW flow model (e.g. Wahid *et al.*, 2007). The physically based GW flow equation and the unsteady open-channel flow equations are solved either as a single time step (Pinder and Sauer, 1971) or as multiple time steps (Swain and Wexler, 1996; Nobi and Das Gupta, 1997; Nobi, 1994). It is thus recognized that the simultaneous solution of the groundwater flow equation and the unsteady open-channel flow equations overcomes many of the drawbacks attributed to the single model approach. However, this approach may demand a computational effort that cannot be fully justified in cases where stream flows show smooth variations or when the objective of the study is just to determine the average system behaviour over a period of time that largely exceeds the response time of the surface component (Rodríguez *et al.*, 2006). In those situations, MODFLOW allows simulation of river-aquifer interactions by means of alternative add-on packages. The original river package (RIV) considered constant riverheads and no variation in river flows (McDonald and Harbaugh, 1988). This package was later surpassed by the STREAM package developed by Prudic (1989) under the new MODFLOW 2000 structure (Harbaugh *et al.*, 2000), which introduces a mass balance computation for river-aquifer flows to calculate the river stages. MODFLOW continues to be a commonly applied tool for approaching the diverse flow problems of GW-SW systems. Relatively little published work investigates stream-aquifer interactions in an area where the tidally dominated surface water characterized by high salinity and the water is extensively extracted from underground aquifers. Such a condition exists in the southwestern coastal region of Bangladesh, where the rivers and underground aquifers are dynamically linked to each other (Nobi, 1994; Nobi and Das Gupta, 1997; Mirza and Sarker, 2004; Adhikary, 2009). However, Jolly *et al.* (2008) provided a detailed review of GW-SW interactions in arid and semi-arid wetlands and the impact of salinity on the wetland ecology. Since GW-SW systems are not the isolated components of the hydrologic system, but instead interact in a variety of physiographic and climatic landscapes, so the river-aquifer interaction is at the very core of the hydrological cycle. Since the river systems in the southwestern Bangladesh have already been affected by the salinity contamination (Nobi, 1994; Mirza and Sarker, 2004; Adhikary *et al.*, 2011), the dynamic flow exchanges may have high potentials to affect the GW system through dynamic interaction process. Therefore, an understanding of the dynamic interaction mechanism between the river and underlying aquifer is indispensable for solving the water resources problems in this region. Thus, the major objective of this study is the investigation and assessment of the river-aquifer interaction process between the coastal river and shallow unconfined aquifer in the southwestern region of Bangladesh. The obtained results in this paper can be used as a supplementary reference for further research of better understanding on salinity intrusion mechanism, which surely provides useful information for developing the appropriate GW resources management strategy in this region.

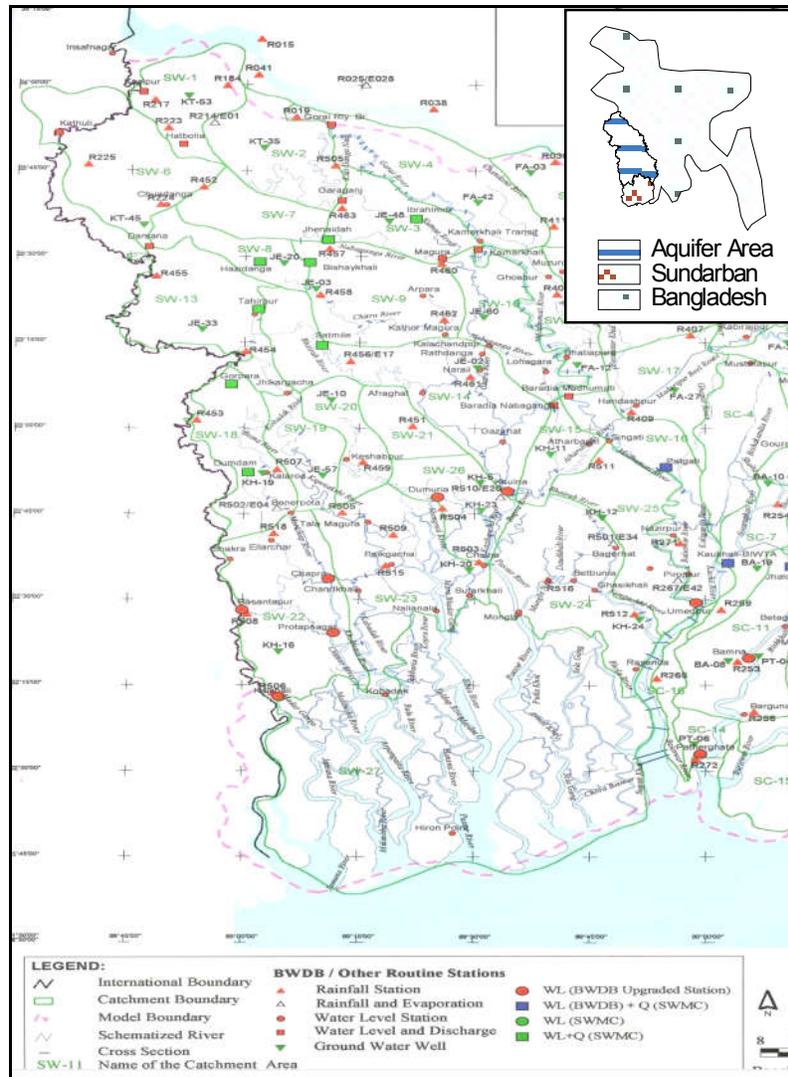
## 2. OVERVIEW OF THE SOUTHWESTERN REGIONAL AQUIFER

### 2.1 Location and Topography

The study area is situated in the south-west region of Bangladesh lying between 22.20<sup>0</sup> to 24.12<sup>0</sup> north latitudes and between 88.56<sup>0</sup> to 89.98<sup>0</sup> east longitudes. The area covers about ten administrative districts of Khulna division under the jurisdiction of three greater districts such as Khulna, Jessore and Kushtia in the southern Bangladesh. The area is surrounded by the Ganges-Padma River in the north, the Gorai-Madhumati-Haringhata-Baleswar River system in the east, the international border between Bangladesh and India in the west and the Bay of Bengal in the south (Figure 1). The whole southwest region of Bangladesh has been sub-divided into 27 hydrological catchments by the Institute of Water Modeling (IWM), Bangladesh during regional model development phase (Figure 1). The present study area attempts to use the same basin delineation made by IWM, which is enclosed by 20 catchments and it covers a total area of about 16985 sq. km. in the southwestern Bangladesh.

Usually, the natural GW table follows the topography of the area to be modelled. In order to establish the topography of the area, the digital elevation model (DEM) of the study area have been developed from the public domain CGIAR-CSI SRTM database (Jarvis *et al.*, 2008) reproduced and made publicly available by The Consultative Group for International Agricultural Research (CGIAR) Consortium for Spatial Information (CSI) and Shuttle Radar Topographic Mission (SRTM). The DEM data is then processed in the framework of ArcGIS

software to obtain the topographic map of the study area, which is presented in Figure 2. The study area DEM reveals that the area is dominated by flat topography. It varies from 18 m to 2 m above mean sea level (MSL) with a gradual drop from northwest towards southern coastal-belt directions. At extreme south, the coastal part has very low and flat topography varying between 0 m to 2 m above MSL.



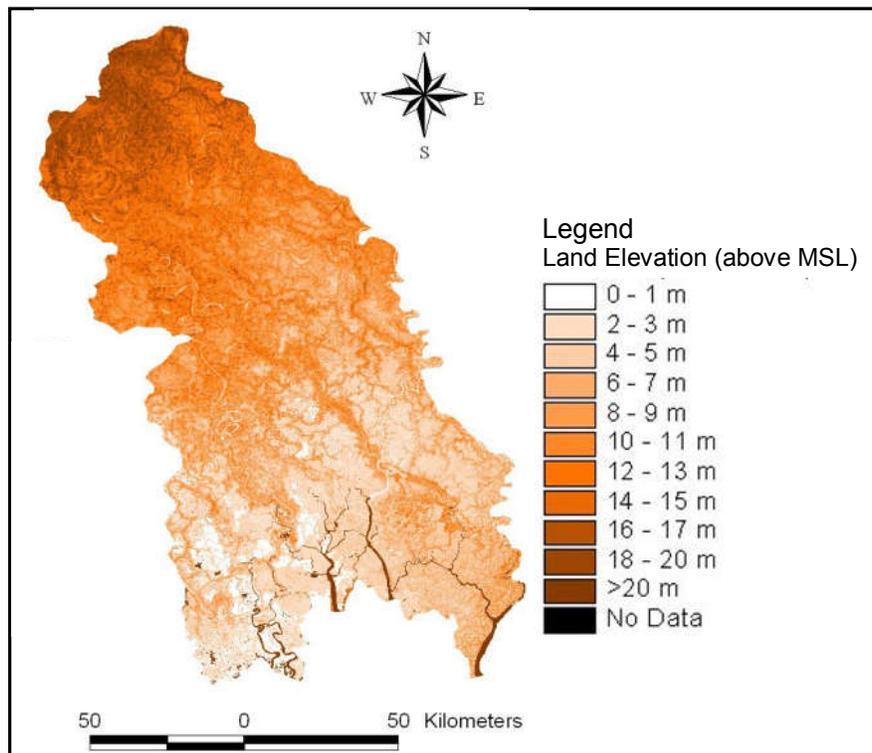
**Figure 1** Study area showing the river systems and hydrological monitoring stations

## 2.2 Climatic Characteristics and River Systems

The annual average rainfall is 2000 mm of which approximately 75% occurs during the monsoon season (June to September) and almost 90% occurs in the wet period (April to September). The mean annual temperature is 26°C. However, rainfall in the area varies from north-west to south-eastern direction. The relative humidity also varies from 70% in March to 89% in July. Depending on these parameters, the average pan evaporation is also high and generally exceeds the rainfall rates in dry season (October to March). In general, the climate is favourable for agriculture across the area throughout the year. Like other parts of Bangladesh, irrigation is the main land use pattern in the southwest region. The coastal part of the area is characterized by a number of shrimp culture farms (Adhikary, 2009).

The study area is demarcated by the courses of the major river bounding the area, the Ganges-Padma River in the north and the Gorai-Madhumati-Haringhata-Baleswar River system in the eastern side, which flows to the Bay of Bengal in the south (Figure 1). The boundary river Gorai spills into several distributaries which cross the area

giving access to freshwater and maintaining internal drainage channels. The freshwater flows come into these river networks mainly through the Gorai River originating from the Ganges in the northwest corner of the area. Notable inland rivers such as the Nabganga, Kumar, Kobadak and Bhairab serve as essential drainage channels that are generally at a lower level than the regional rivers. In dry season, the Ganges River in the upstream is main source of freshwater. For these rivers, rainfall serves as another source of freshwater during monsoon period. These perennial river systems also receive base flow from the GW in underlying aquifer system during dry season (Halcrow, 1993). The tidal areas located in the southern coastal part are characterized by large estuaries formed by the Passur, Sibsa, Malancha and Ranimangal or Haribhanga River which are also interlinked by numerous smaller channels. Apart from the major river systems, several minor channels and creeks grown up within the region contributing surface runoff to the main system. In dry season (November to April), the greatly reduced flow in the Gorai River allows saltwater to penetrate far inland through the tidal channels located in the downstream. The central part of the area also receives very little amount of freshwater flows from the major rivers during the dry season. Under normal conditions, the extreme southwest portion at Sundarban area doesn't receive freshwater flows from the major rivers and maintains a constant level of salinity (Khan, 2002; Mirza and Sarkar, 2004).



**Figure 2** Topography (DEM) of the studied aquifer located in southwestern Bangladesh

### 2.3 Geological Setting

The southwest region of Bangladesh is underlain by alluvial sediments of the Bengal Basin, laid down by the Ganges-Brahmaputra River system. The sediments become progressively older with depth and lithologically range from clay and silt, to fine, medium and coarse sand, which are unconsolidated or lightly compacted. Only those sediments down to 300 m depth are of interest hydrogeologically. Previous studies conducted in the study area (Nobi, 1994; Halcrow, 1993) reported that there are no faults or folds within these hydrogeologically significant sediments. In general, the upper clay layer is comparatively thick in the coastal part. In most of the areas, the composite and deep aquifer sequences are found in the 150 to 300 m depth range. The upper surface layer of mainly clay and silt characterized by high porosity but low permeability, which has poor aquifer properties and thus unsuitable for significant GW development. The intermediate layer has moderate to good aquifer properties and capable of producing reasonable amount of water. However, the main aquifer (lower unit) is the most important source of GW for irrigation, which is characterized by high porosity and moderate to high permeability and thus, it can provide large quantities of water to shallow and deep tube wells.

### 3. METHODOLOGY

#### 3.1 Setting of Hydrogeological Framework

The conceptual model helps to simplify the actual field problem and to organize the associated field data so that the system can be analyzed more readily (Elkrail and Ibrahim, 2008). A total of 52 borelogs are available in the GW circle (GWC) of Bangladesh Water Development Board (BWDB) covering the whole study area containing individual layer lithology along the depth. This allows taking the full advantage of GW Modeling System (GMS) to build a conceptual model within its software framework. GMS is a graphical user interface (GUI) for using MODFLOW along with its associated add-on packages (Harbaugh et al., 2000; McDonald and Harbaugh, 1988) and stratigraphic modeling options of the aquifer systems. It has a powerful GIS interface for use in different phases of GW modeling. Interpretations of individual lithology followed by semi-automatic preparation of cross-sections and automatic fence-diagram reveals that an unconfined aquifer exists up to 150 m below the ground surface characterized by two distinct aquifer layers (Figure 3) throughout the whole study area. The developed conceptual model is then transferred to numerical environment by using USGS finite-different MODFLOW code in the GMS software framework for subsequent simulating works.

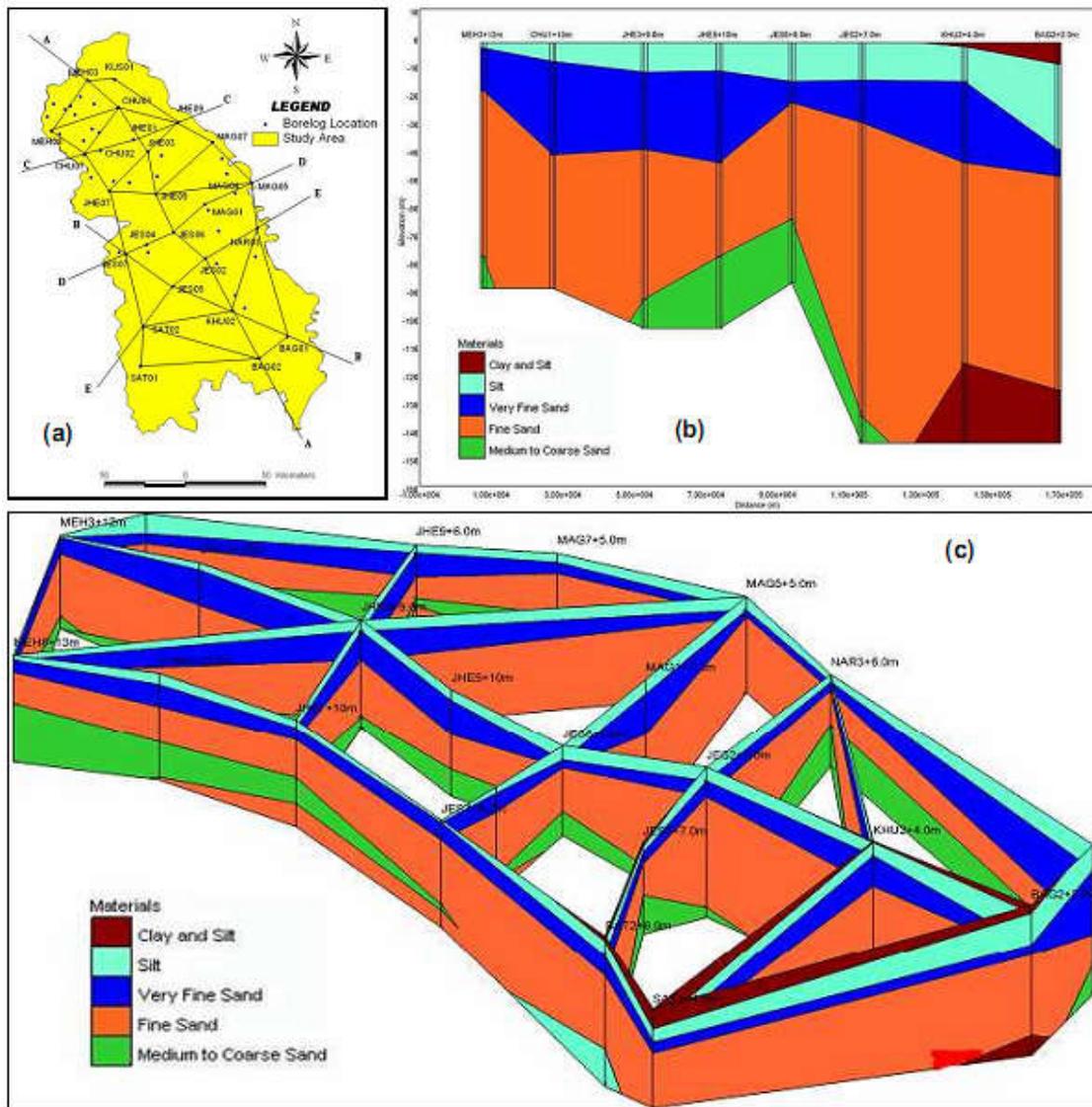


Figure 3 (a) Location of borelogs (b) Hydrogeological profile along N-S direction (A-A) (c) Fence diagram

All the available spatially distributed data such as location of GW level monitoring well, recharge, aquifer hydraulic parameters, top and bottom surface of two aquifer layers, bottom of riverbed etc. is mapped using ArcGIS software by digitizing point data, line or polygon features. The topography of the upper layer is spatially variable from north to south direction and is assigned into the model by integrating the DEM of the study area by krigging technique. The surface topography has influence on the head pattern of the upper aquifer layer and frequently receives rainfall recharge. The hydrogeological setting of the study area is characterized by large horizontal and vertical heterogeneity. Mainly three external sources of water influence the recharge conditions of the flow system such as rainfall recharge, later inflow from west boundary and river bed leakage in some sections.

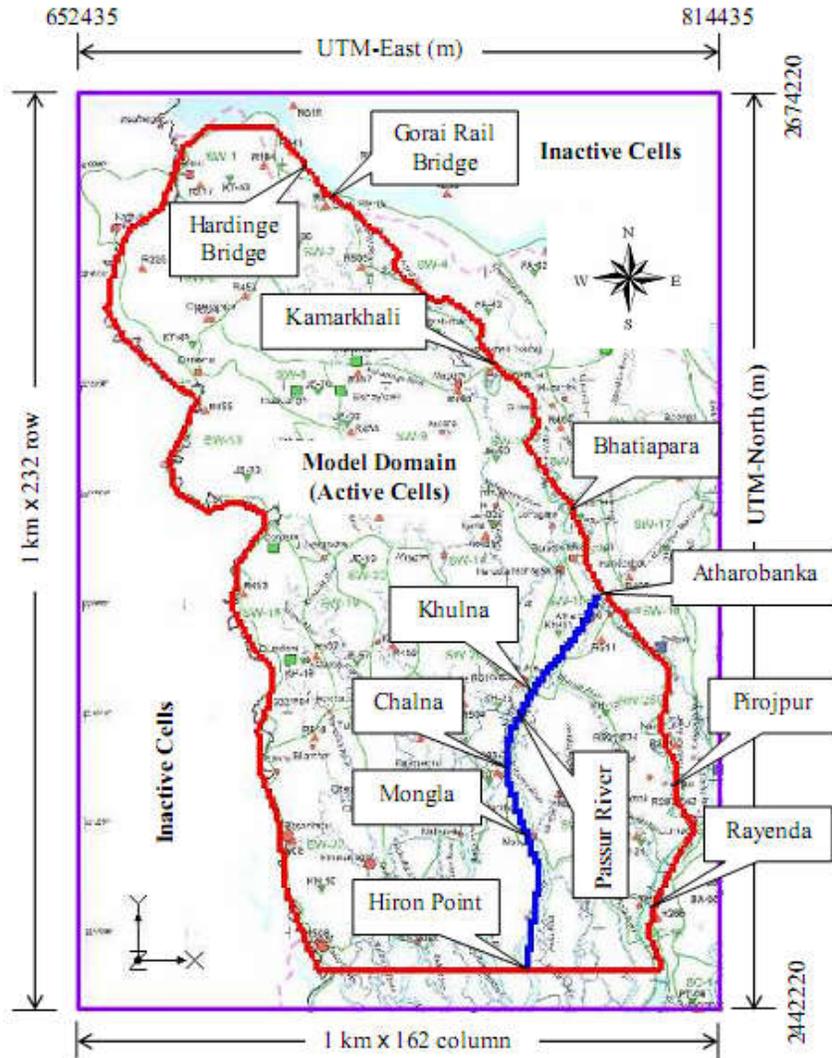


Figure 4 Location of model domain for the studied aquifer

### 3.2 Development of Numerical Model for Integrated River-Aquifer System

The objective of the numerical model construction is to check and assess the validity of various interpretations regarding the flow system. These include (i) the location and type of flow-system boundaries, (ii) the location of recharge areas and (iii) variations in interpretation of hydrogeological framework. The three-dimensional GW flow model MODFLOW-2000 (Harbaugh *et al.*, 2000) and its add-on river simulation package (RIV) (McDonald and Harbaugh, 1988) are used for developing the integrated river-aquifer model in the numerical environment of GMS software framework. MODFLOW computes the hydraulic heads and cell-by-cell fluxes during the GW flow simulation. For simulating the GW flow in the integrated river-aquifer system, a regularly spaced, finite-difference grid structure of the model domain is constructed. Each cell in the model grid is faced

into three directions. The model grid is placed in such a way that model column is aligned with the principal direction of GW flows, which is mainly seaward direction based on the topography. Thus, the X, Y and Z-axis of the model grid are placed along the east-west, north-south and top-bottom directions, respectively for conducting three-dimensional GW flow simulations. In order to prepare the finite-difference model grid, the aquifer system domain has been divided into 232 rows and 162 columns, with each cell having 1 km x 1 km square grid size in the horizontal plane consisting of total 75168 cells in the two layers of the model domain. The model consists of two aquifer layers (up to 150 m depth) based on the stratigraphic analysis and simulating the principal hydrostratigraphic units presents the upper regional unconfined aquifers. The top layer (layer no. 1) is characterized by composite mixtures of clay, silt, very fine sand and fine to medium sand and lumped into one unit (0-60m). The bottom layer (layer no. 2) is represented by relatively coarser materials like fine, medium and coarse sand lumped into it (60-150m) (Figure 2). However, both layers are hydraulically well connected to each other in vertical plane (Halcrow, 1993; Nobi and Das Gupta, 1997). The simulation period for the flow model is taken as 14 years from 1992 to 2005 based on data availability. The whole simulation period is divided into 28 stress periods having two periods (wet and dry) in a year (El Yaouti et al., 2008). GW recharge is assumed to occur only in the wet period (May to October) and no recharge is considered in dry period (November to April) based on rainfall data analysis and hydrological characteristics in Bangladesh. Each stress period is further divided into six time (one month) steps with a total of 168 time steps. Thus, each time step consists of 30 days with a total simulation period of 5113 days in this study.

Surface and bottom elevations of both layers are interpolated from DEM and boreholes data, respectively. The model boundaries are represented by the available hydrological features adjacent to and within the model domain (Figure 4). A time dependent specified head boundary is applied along the Ganges River in the north side and Gorai-Madhumati-Haringhata-Baleswar River systems in the eastern side of the study area using water level data of different gauging stations. In the south side, the model boundary is extended up to Hiron point to establish the sea boundary and a time dependent specified head boundary is provided using the Hiron Point water level measurement. The west boundary of the model domain is located along the international border between Bangladesh and India and a general head boundary is assigned along this side. For this purpose, the known hydraulic heads from the observed GW level of several monitoring wells located along the border is used. Only a coastal river named Passur River is incorporated in the model domain by using the river simulation package (RIV) of MODFLOW. This river is one of the distributaries of the Gorai-Madhumati River, which flows over the study area and finally flows to the sea. The location of Passur River in the model domain is presented in Figure 4. For integrating river with the aquifer model, the bottom elevation of the riverbed is assigned from the bathymetry data of the Passur River. River is integrated in the model domain in the top layer only based on its bathymetry data. The recharge rates estimated by Halcrow (1993) based on long-term water balance study were assigned on the top layer only using the MODFLOW recharge package. There was a lack of enough pumping test data in the area to be used as aquifer hydraulic property. Therefore, the hydraulic conductivity is initially distributed on the basis of available pumping test data and lithological knowledge obtained from the collected borelogs data.

### 3.3 Conceptualization of Interaction Process in an Integrated River-Aquifer System

Assessment of dynamic flow exchanges between the river and underlying aquifer is based on the concept that usually, the rivers and streams contribute water into the underlying aquifer system or get water from it depending on the head gradient between the rivers and the GW regime. The mechanism of this interaction process can be described by using Darcy's law (McDonald and Harbaugh, 1988). Assuming uniform flow between rivers and aquifer systems, the dynamic interaction can be mathematically represented by applying the concepts of Darcy's law, which can be expressed as in Equation (1).

$$q_n = C_n(H_n - h_n) = \frac{K_n A_n}{D_n}(H_n - h_n) = \frac{K_n W_n L_n}{D_n}(H_n - h_n) \quad (1)$$

Where,

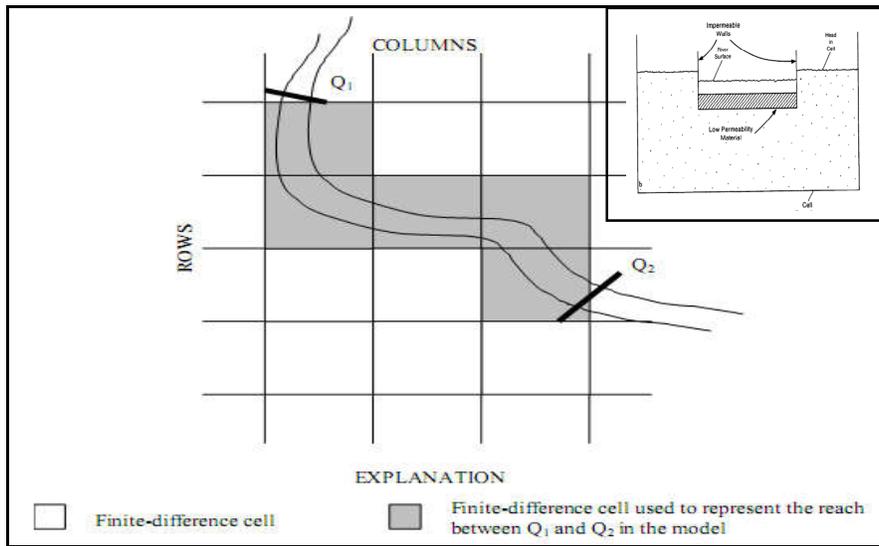
- $q_n$  = Simulated flow rate at a single cell ( $L^3T^{-1}$ )  
(negative for flow out of the groundwater system)
- $C_n$  = Conductance of the bed material separating the surface water body (river) from the groundwater system ( $L^2T^{-1}$ )
- $K_n$  = Hydraulic conductivity of the river bed material ( $LT^{-1}$ )
- $D_n$  = Thickness of river bed material (L)
- $A_n$  = Area of water body within the finite difference cell ( $L^2$ )

- $W_n$  = Width of the river in the finite difference cell (L)
- $L_n$  = Length of the river reach in the finite difference cell (L)
- $h_n$  = Computed hydraulic head for finite difference cell n (L)
- $H_n$  = Water level in the river or surface water body (L)

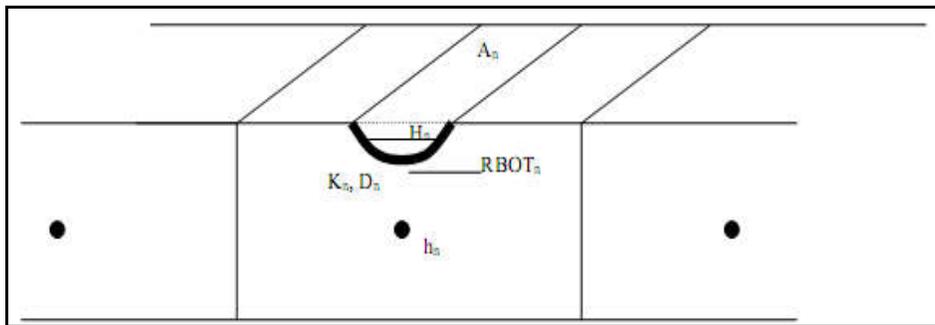
The dynamic flow exchange between rivers and aquifers can be computed by coupling the river (RIV) package with the GW flow model developed by using the MODFLOW code. The conceptualization applied in river package (RIV) of MODFLOW (McDonald and Harbaugh, 1988) is presented in Figure 5. In the RIV simulation package, flow at each finite difference cell specified is computed by using equation (1) and the calculation principle is presented in Figure 6. In the river simulation package (RIV) of MODFLOW code, mathematically the equation (1) can be expressed by two different equations such as equation (2) and equation (3).

$$q_n = C_n(H_n - h_n) \quad \text{for } h_n > RBOT_n \quad (2)$$

$$\text{or, } q_n = C_n(H_n - RBOT_n) \quad \text{for } h_n < RBOT_n \quad (3)$$



**Figure 5** Conceptual representation of river reach by finite difference cells in MODFLOW

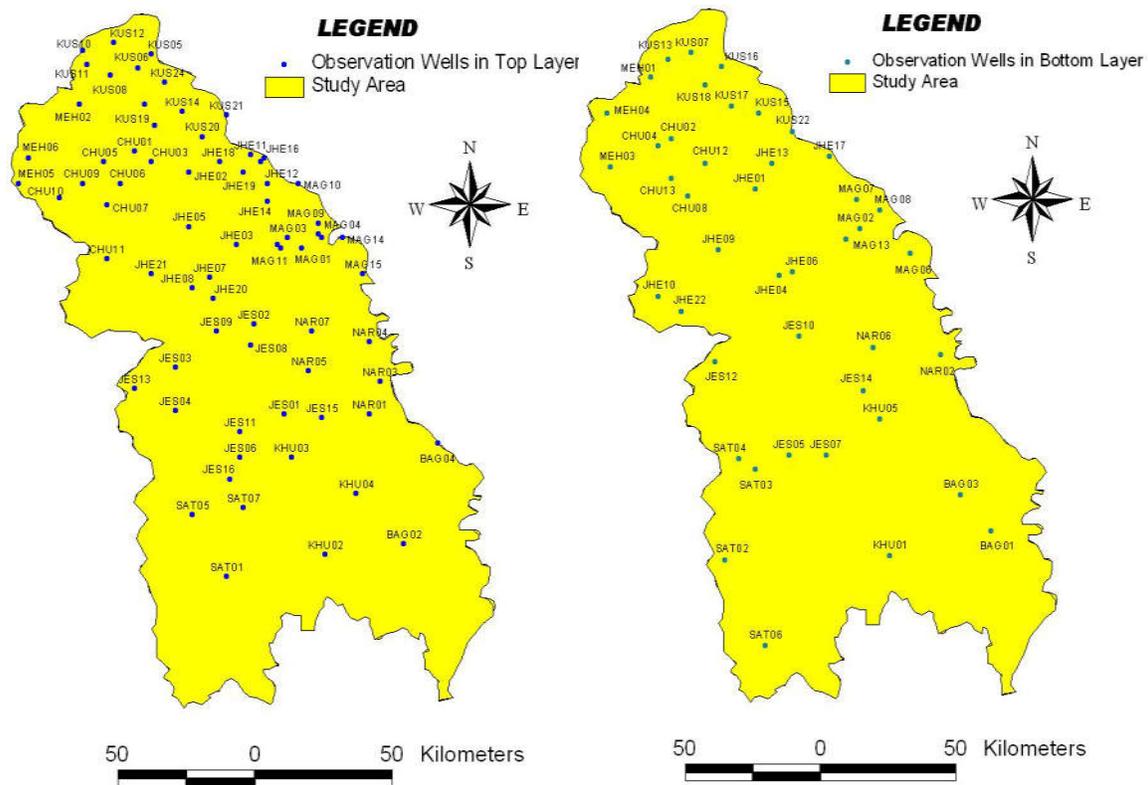


**Figure 6** Basic principle of flow exchange between river and aquifer system

**3.4 Model Calibration in Steady State Condition**

Initially, the developed GW flow model is simulated and calibrated under steady-state condition for the average base condition in 1992. The observation data used in the calibration process was the water table elevations from the GW level monitoring wells. Although, steady-state condition does not occur in the practical field situation, but it gives a very initial estimates of model parameters. It also helps to check the mass balance and to check the assigned boundary conditions in the model. Steady-state simulation was run to estimate the initial head

distributions to be used in the transient simulation (Nobi, 1994; Anderson and Woessner, 1992). Model calibration in GW modeling is often required because of the unavailability of reliable field measured data to estimate the aquifer flow characteristics. During calibration, traditional trial and error technique is followed. GMS has a powerful graphical user interface (GUI) with strong GIS linkages for assigning model parameters either into cell-by-cell or zonal based approach. However, in this study, model parameters are assigned into the model by dividing the whole model domain into a number of zones for both layers assuming similar hydrogeological properties, since the cell-by-cell input is a complicated task especially in a large GW model. In steady-state calibration, the initial values were adjusted within a reasonable limit to obtain a good agreement of the computed and observed water table in 1992 and quantified by statistical means. However, the developed integrated river-aquifer model is calibrated and validated against the observed water level from total 114 monitoring wells having 71 wells in top layer and 43 wells in bottom layer (Figure 7) of the aquifer. The calibrated hydraulic conductivities (20 zones) vary from 9 to 14 m/day for top layer and 18 to 40 m/day for bottom layer.

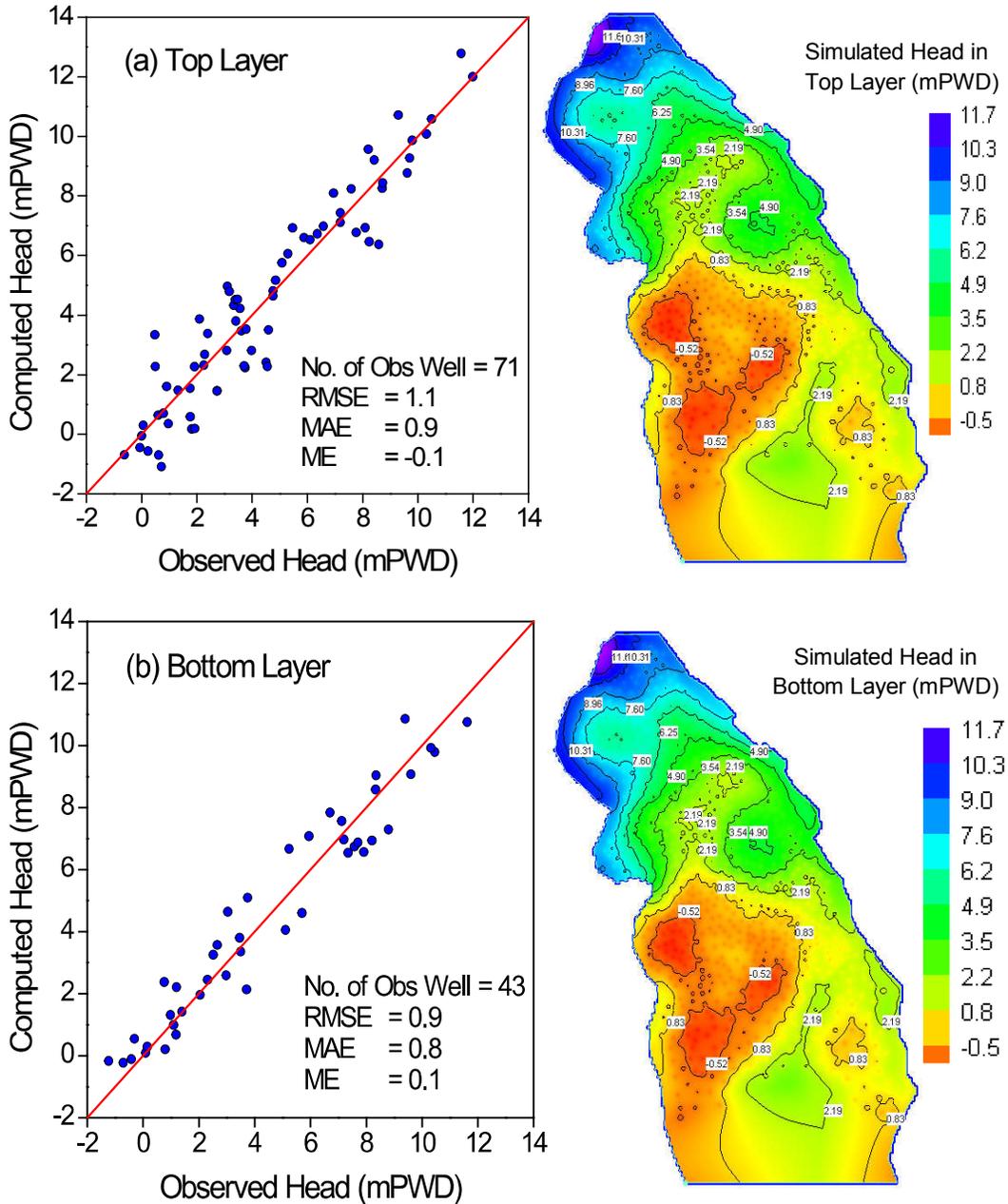


**Figure 7** Location of monitoring wells in top and bottom layers used for model calibration

During model calibration, the riverbed conductance is required, which has been conservatively assumed as 50% of the hydraulic conductivity of the underlying aquifer cells. It can be mentioned here that large values of riverbed conductance can be assumed in absence of actual field data (El Yaouti et al., 2008; Nobi and Das Gupta, 1997) to ensure a good hydraulic connection between river and underlying aquifer system. Accordingly, the same recommendation has been followed in this study. To evaluate the calibration performance, scatter diagrams are prepared for each layer and a 45° calibration line is drawn to represent the perfect correspondence between observed and simulated values. However, the model is considered calibrated, if the residuals of the model are closer to zero. Spatial distributions of observed and computed GW heads are presented in Figure 8, which demonstrates the satisfactory level of model calibration. In addition, three error parameters such as root mean square error (RMSE), mean average error (MAE), and mean error (ME) have been calculated to check the adequacy of the parameters calibration. All estimated errors for both top and bottom layer are very close to zero, which proves that the developed model is reasonably calibrated under steady state condition (Figure 8).

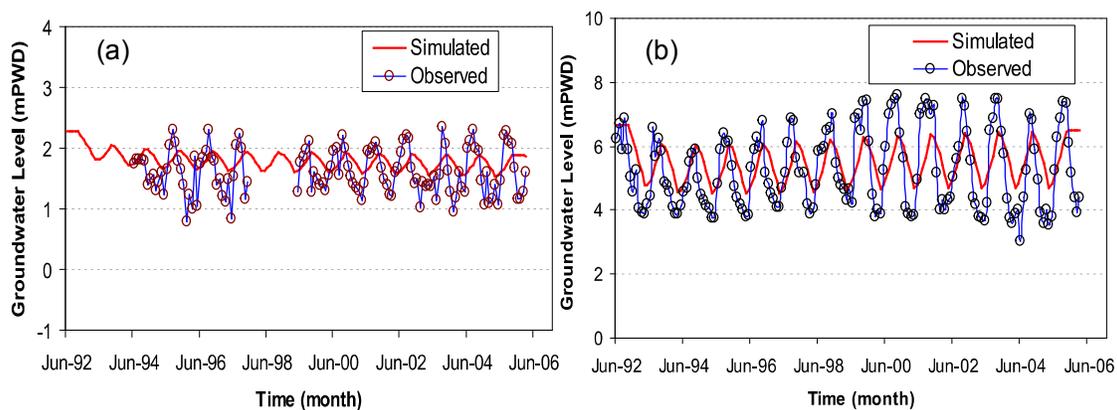
**3.5 Model Calibration in Transient State Condition**

The transient simulation was run to replicate the flow characteristics in the aquifer by introducing the pumping well. The discharging through the pumping well was simulated as specified flow boundary using specified pumping rate. The pumping well is considered a sink and is represented in the model by a node. Initially, model calibration is performed using the available observed water table data for a period of 1992 to 2002. The remaining data from 2003 to 2005 is used for validation purpose. The whole simulation period is divided into 28 stress periods containing two periods (dry and wet) in a year. Based on the study conducted by El Yaouti *et al.* (2008), GW recharge is assumed to occur only in wet period (May to October) and no recharge is considered in dry period (November to April) based on rainfall data analysis. Each stress periods are further divided into 6 time steps with total 168 time steps. Thus, each time step consists of 30 days with a total simulation time of 5113 days. In transient analysis, the head distributions or aquifer response at different simulation periods under existing stresses are found out.



**Figure 8** Simulated head distributions in the (a) top and (b) bottom layer in the developed GW model

Transient calibration is carried out using the same model parameter structures and initial head distributions computed in steady state calibration. During transient calibration, storage parameters are assigned in the same zone for both layers. The observed and simulated heads are then carefully compared and parameters are adjusted by trial and error method to obtain a good agreement between them. Initially, storage parameters are adjusted to obtain good match. In addition, vertical conductivity is adjusted very little. The horizontal hydraulic conductivity was not changed. However, only one parameter is adjusted at a time because it facilitates to understand the effect produced by the change of each parameter. After modifying of parameters every time, the model is re-run. Several simulations have been carried until a good match between observed and simulated heads are obtained. From transient analysis, it is observed that without modifying the horizontal hydraulic conductivity values good match between observed and computed heads is obtained, which depicts that reasonable calibration was achieved in the transient-state. It is found that most of the observation wells show better agreement with the computed heads and the calibrated hydrograph follows the average trend of the observed hydrograph. The calibrated GW level hydrograph for two representative monitoring wells are presented in Figure 9. The calibrated values of storage coefficient vary from 0.002 to 0.004 for both layers. However, there are some monitoring wells where poor agreement between observed and simulated heads is noticed. The study area constitutes a large number of small rivers and water bodies, which have influence on GW level. However, practically, it is quite impossible to incorporate all these in the model domain. It may also be due to aquifer anisotropy and heterogeneity. Sensitivity analysis shows that response of the modelled system is more sensitive to recharge variations than hydraulic conductivity and storage parameters.

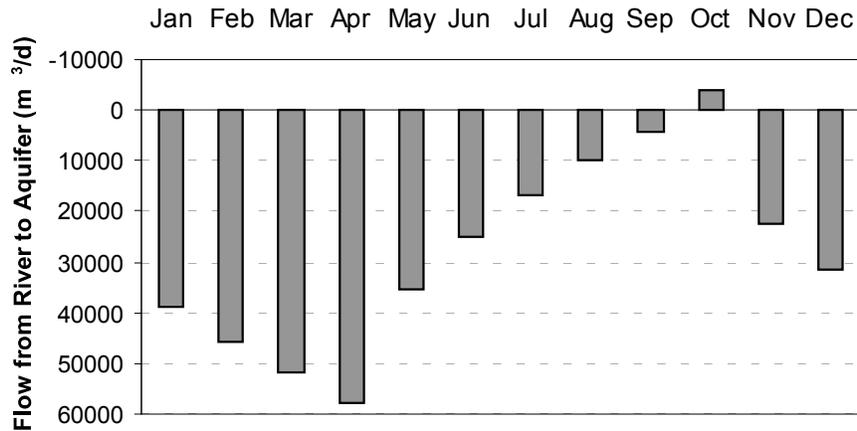


**Figure 9** Simulated and observed GWL hydrograph for (a) top layer (BAG 04) and (b) bottom layer (JHE 17).

#### 4. ASSESSMENT OF RIVER-AQUIFER DYNAMIC INTERACTION

In this study, assessment of dynamic flow exchanges between the river and aquifer is based on the concept that usually, the rivers and streams contribute water into the underlying aquifer system or get water from it depending on the head gradient between the rivers and the GW regime. The river simulation package (RIV) of MODFLOW code simulates the flow exchanges for the integrated river-aquifer model, which is representing the dynamic interaction between the aquifers and rivers. Water levels in the rivers were used from the different gauging stations within it. The developed integrated river-aquifer model is first calibrated and validated against the observed water level from total 114 monitoring wells having 71 wells in top layer and 43 wells in bottom layer of the aquifer (Figure 7). At the same time, riverbed conductance parameter is also calibrated. Finally, the dynamic flow exchanges between the river and the aquifer system is simulated for the whole simulation period from 1992 to 2005 and mean flow exchanges by the dynamic interaction process is evaluated. The dynamic flow exchange between river and its underlying aquifer is often very important in many water resources problems such as the problems the present study deals with. As the rivers system in the study area is already affected by the saline water, the dynamic flow exchanges can greatly influence the salinity of the GW system by contributing salinity through dynamic interaction. Keeping this in mind, an attempt has been made to estimate the river-interaction process in the present study. During the simulation of dynamic interaction, the riverbed conductance value is required which has been conservatively assumed as the half (50%) of the hydraulic conductivity of the underlying aquifer cells (Nobi and Das Gupta, 1997). However, according to El Yaouti et al. (2008), large values of river bed conductance can be assumed in absence of actual field data to ensure a good hydraulic connection between river and aquifer system. From the simulation result, it is observed that most of the observation wells show good agreement with the computed heads and the calibrated hydrograph (Figure 8 and Figure 9) follows

the average trend of the observed hydrograph. Thus, the developed integrated river-aquifer model satisfactorily simulates the flow characteristics of the regional GW system.



**Figure 10** Mean monthly flow exchange (dynamic interaction) between the Passur River and underlying aquifer

The river-aquifer dynamic flow exchange is simulated for the whole simulation period from 1992 to 2005 and the dynamic interaction is found to be quite significant. In dry season, there is no surface runoff into the rivers and dry season flow comes into the river from the underlying aquifer. The simulated mean monthly flow exchange for the whole simulation period of 14 years from 1992 to 2005 are presented in Figure 10. Positive sign refers that flow is entering from the river into the aquifer and negative sign refers that the flow is contributed by the aquifer into the river system. The obtained result reveals that any dissolved contaminants may enter into the underlying aquifer to meet fresh GW system and pollute it accordingly. It has a great significance in the field of contaminant hydrology and relevant fields. However, although some findings are qualitative here, the model provides a better understanding of the coupled river-aquifer system and the potential causes of shallow GW pollution by contaminated recharge water in the coastal area. Modeling result also demonstrates that fluctuations of hydraulic heads are dependent on seasonal variations of recharge from rainfall and riverbed leakage. In addition, the river-aquifer relationship is proved to be very responsive to water table fluctuations, which interprets the losing or gaining characteristics of river reaches.

## 5. CONCLUSIONS

This study concludes that the methodology illustrated in the study will open a window for better understanding of the integrated river-aquifer system and the potential causes of polluting the shallow GW resources in the underlying aquifer by recharging the saline water in the coastal area of south-western Bangladesh. The study conclusively proves that the dynamic interactions between the rivers and the underlying aquifer systems in the integrated river-aquifer systems in the coastal region have significant influence on the changing flow characteristics within the overall system. The study also concludes that there is a great possibility of saline water encroachment into the GW system through recharging process following the dynamic interactions. The findings of this study are expected to be useful for developing appropriate SW and GW resources management program in the coastal zone of Bangladesh. The developed model may be used in the through understanding and assessment of the salinity intrusion mechanism in a dynamically interlinked river-aquifer system especially in the coastal area of Bangladesh in future.

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