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Assessment of Interactions between River and Aquifer in the Gowri-hole Sub-catchment

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ABSTRACT

Surface water interacts with groundwater in many types of physiographic and hydrogeological conditions. Exchange of water varies spatially and temporally due to the effect of natural and anthropogenic factors. Interactions between a river and the underlying aquifer systems are often difficult to observe and measure. The objective of the present study is to analyze the spatial and temporal variation of river-aquifer interactions in the Gowri hole sub-catchment and quantify the amount of flow exchange between river and aquifer. In the study, a new conceptual model is developed using RIVER package of Three-Dimensional Finite-Difference Modular Groundwater Flow Model (MODFLOW) for the simulation of river-aquifer interaction processes. The sub-catchment of Gowri hole, which is a tributary of Kumaradhara river spread across an area of 134 km^2 is considered. The model was calibrated from June 2004 to May 2010 under the transient condition with a daily step input of all necessary hydro-geological data. The calibrated model was validated from June 2010 to October 2012 from two monthly observation wells of Department of Mines and Geology and one seasonal observation well of Central Ground Water Board (CGWB). Gowri hole acted as a gaining river during the monsoons due to aquifer discharge and acted as a losing river due to river leakage during post-monsoon and summer months. River leakage continued to occur upto the end of summer months resulting in fragmentation of few river segments. Aquifer discharge sustained to exist even in the summer period avoiding the low flow river segments from drying.

INTRODUCTION

Surface water interacts with groundwater in many types of physiographic and hydro-geological conditions. The nature and degree of connection describe the scope of water availability in the systems. The quantity and quality of these resources affect each other due to the interconnectivity (Kalbus et al., 2006). The interactions between a river and the underlying aquifer systems are dynamic. Water from an entity travels to the other one according to the variation in hydraulic gradient. Exchange of water varies spatially and temporally due to the effect of natural and anthropogenic factors. Inconsistent climate and seasonal variability in precipitation influence the availability of water over a catchment area. Anthropogenic activities, such as groundwater withdrawals and land use practices perturb groundwater and river stage relationships by varying the hydraulic gradients (Ivkovic, 2006). It may further lead to flow variability in the river, which adversely affects the complex dynamic equilibrium of the basin (Shekar, 2016). Groundwater-surface water (GW-SW) interactions are often difficult to observe and measure. Consequently, the process remains poorly perceived in many catchments of the world (Ivkovic, 2006). It is essential to identify and quantify the surface water and groundwater exchange processes for sustainable river basin management (Kalbus et al., 2006). Basic knowledge of the principles and mechanisms of interactions is fundamental to understand the influence of interactions (Ivkovic, 2006). Many efforts were made in recent years to approximate the interaction from relatively straightforward analytical methods to complex numerical solutions. Depending on the purpose of the study, suitable methods were adopted for the respective spatial and temporal scale (Kalbus et al., 2006).

The numerical model MODFLOW is an extensively used finite-difference groundwater flow model for addressing flow problems of GW–SW systems (McDonald and Harbaugh, 1988). MODFLOW provides various options to consider time independent and space dependent data. It consists of multiple packages for simulating different components of a groundwater system with the capability of modifications. Many researchers demonstrated the applicability of the RIVER package of MODFLOW for simulating the river-aquifer relationship at river reach scale (Martínez-Santos et al., 2010), sub-catchment scale (Haque et al., 2012), catchment scale (Sanz et al., 2011; Alam and Umar, 2013) and regional scale (Adhikary et al., 2012; Rassam et al., 2013). Dynamic flow exchange values obtained from flow budget proved to be very sensitive to groundwater level fluctuations due to increased groundwater abstraction. Although the results were qualitative, river-aquifer relationships confirmed to exist from the interpretation of flow budget values.

Previous studies of interaction were conducted on regional, catchment and river reach scale. Little attention is given on the sub-catchment scale of a river basin. The interaction process in the sub-catchment scale finds it challenging because of the intermediate scale size. In contrary, the scale has importance in the sustainable management of water resources in the area. There is no lack of hydrological models for the assessment of GW-SW exchanges. However, insightful application of numerical models to study both spatial and temporal variability of interactions is lacking. The objective of the study is to analyze the spatial and temporal variation of river-aquifer interactions in the sub-catchment scale of Gowri hole and quantify the amount of flow exchange between river and aquifer.

STUDY AREA

Figure 1 shows the sub-catchment area of Gowri hole, which is a tributary of Kumaradhara river. It flows and join river Nethravathi, a major west-flowing river of Karnataka, India. Gowri hole is a 4th order stream resulting from the confluence of Madalu hole and few other streams taking birth at Aivarnadu and Kalmadka. The sub-catchment covers an area of 134 km^2, geographically spread between 12°37' to 12°46' north latitudes and 75°16' to 75°28' east longitudes. The study area being a part of Western Ghats of Karnataka receives an average annual rainfall around 3500 mm. Even though it consists of only one rain gauge station at Aivarnadu, there are quite a good number of rain gauge stations in the adjoining Koila, Panja, and Puttur as shown in Fig. 2. The sub-catchment area is having an undulating topography with hills over the elevated upland area, where streams originate. Streams flow down along the valley slopes to the alluvial plains and join the river flow as Gowri hole towards the outlet. Daily river-stage

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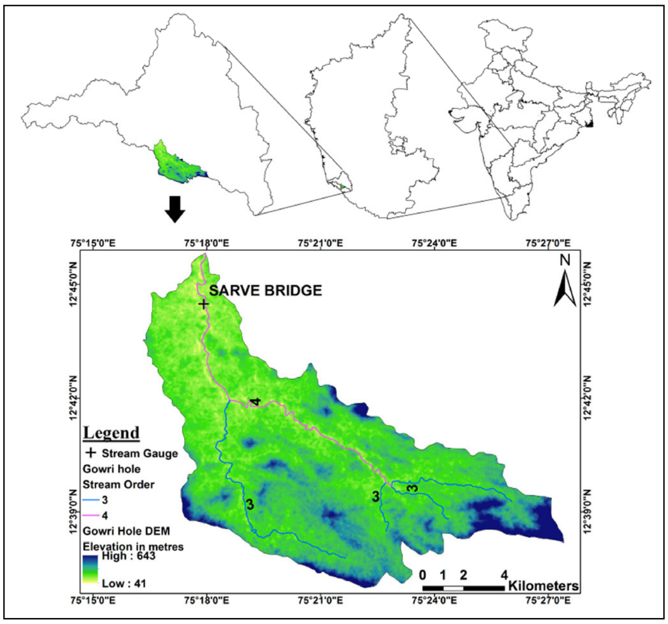

Fig.1. Gowri hole sub-catchment.

and discharge values are measured at Sarve Bridge, located near the outlet.

HYDROGEOLOGY

Figure 2 represents the geological map of the study area, which describes the boundaries of major water-bearing formations. Tonalitic gneiss dominates the study area, which is one of the oldest rock formations. Thick bands of charnockite are also present in some parts of the study area. Groundwater occurs in the unconfined condition of weathered zones of gneiss and charnockite ranging from 5 – 40 mbgl (metres below ground level) and 20 – 30 mbgl respectively. Detailed hydro-geological investigations such as pumping tests were conducted by CGWB in the study area. Pumping test results and aquifer geology give a clear insight into condition of the aquifer and its recharge potential (Kumar et al., 2017).

DATA COLLECTION

Survey of India toposheets of 1:50000 were used for the delineation of sub-catchment boundary, river and stream features of the study area. Geological maps of the Geological Survey of India are used for defining aquifer boundaries. Daily rainfall data was obtained from rain gauge stations located at Aivarnadu, Koila, Panja and Puttur from Karnataka Public Works Department (KPWD). Daily river-stage and discharge data of Gowri hole monitored at Sarve Bridge were taken from KPWD. Groundwater abstraction statistical data such as no. of pumping wells, average daily pumping hours, wells in use, depth of wells, and pumping capacity of wells were collected from the website data.gov.in disseminated by the Ministry of Water Resources, Government of India. Monthly groundwater level observation data of two open wells were obtained from Department of Mines and Geology, Karnataka. Whereas, seasonal groundwater level observation data of one dug well was collected from CGWB for the study. Digital Elevation Model (DEM) data of 1 arc second (approximately 30 m resolution) acquired by Shuttle Radar Topography Mission (SRTM) was downloaded from the official website of United States Geological Survey (USGS).

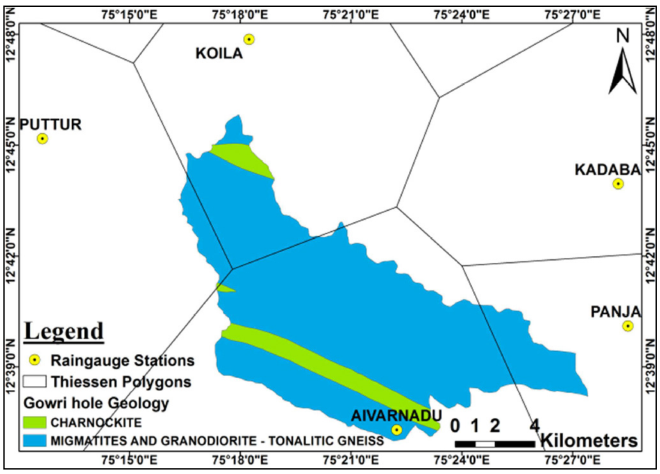

Fig.2. Geological map and rain gauge network.

METHODOLOGY

In the present study, a new conceptual model is developed using RIVER package of MODFLOW to comprehend and analyze the interaction processes at a sub-catchment scale. Groundwater Modeling System (GMS) version 10.0 software is used as a graphical user interface (GUI) for using the finite-difference MODFLOW model. Suitable supporting packages such as WELL, RECHARGE are used for simulating different components of the conceptual model. Also, Layer-Property Flow (LPF) package is selected for defining layer properties such as hydraulic conductivity values and performing flow calculations. Preconditioned Conjugate Gradient (PCG2) is used as a package for solving simultaneous equations based on finite-difference method.

Governing Equations of River-Aquifer Interaction Model

The theoretical background of the interaction model is defined by using Darcy's Law. In the study, the river-aquifer interaction processes are simulated by the RIVER package of MODFLOW through a seepage layer, in which each cell of river feature in the model is defined by a conductance term (Harbaugh et al., 2000) represented as:

$$C_{River} = (K_{River} / B)\, WL \quad (1)$$

Where, L is length of river feature in the modeled cell (m), W is width of the river (m), B is thickness of the river bed sediments (m) and K_{RIVER} is vertical hydraulic conductivity of the riverbed material (m/day).

The river leakage depends mainly on hydraulic conductivity as well as head difference between river stage and groundwater in the area (Rao et al., 2007). The flow from river to the aquifer Q_{RIVER} is defined by equations:

$$Q_{River} = C_{River}\,(H_{River} - R_{Bottom}) \quad \text{for } h \le R_{Bottom} \quad (2)$$

$$Q_{River} = C_{River}\,(H_{River} - h) \quad \text{for } h > R_{Bottom} \quad (3)$$

Where, Q_{RIVER} is flow exchange between river and the aquifer (m^3/day), C_{RIVER} is hydraulic conductance of the seepage layer from Eq. 1 (m^2/day), H_{RIVER} is head of the stream (m), h is head in the grid cell (m) and R_{BOTTOM} is the bottom elevation of the seepage layer (m).

Equation 2 is used for the calculation of river leakage into the aquifer, and Eq. 3 for the calculation of groundwater discharge to the river. The above equations are used to quantify the gain-loss relationship between rivers and aquifers.

MODEL DEVELOPMENT

Conceptual Modeling Approach

The conceptual modeling approach is a process in which data of hydro-geological conditions are accumulated in an organized way to explain interaction processes at a specific area. A new conceptual

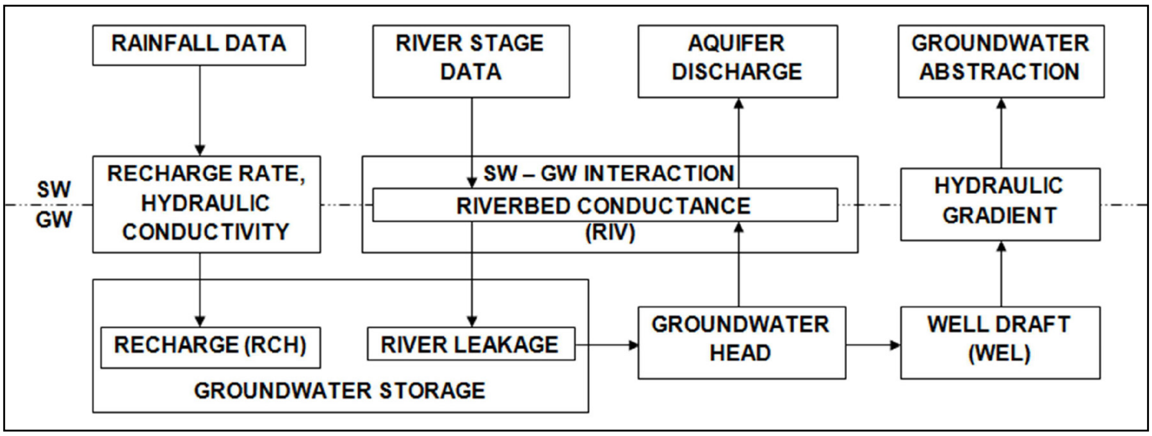

Fig. 3. Conceptual model

model describing the components of the GW-SW system based on theoretical understanding of the interactions is presented in Fig 3.

The interaction between river and aquifer exists through the riverbed as shown in Fig. 3. The surface water input to the groundwater storage is guided by aquifer parameters such as recharge rate, hydraulic conductivity and riverbed conductance. The hydraulic head of groundwater may be either above or below the riverbed elevation depending upon groundwater storage. If it is reasonably below the riverbed elevation, then the condition is called as a losing river. When the groundwater head is above the riverbed elevation, in that case, it is called gaining river.

Aquifer Parameters

Recharge rate was estimated by using rainfall infiltration factor method as per the guidelines suggested by the Groundwater resource Estimation Committee (CGWB, 1997). The ranges of rainfall infiltration factor are presented in Table 1. Hydraulic conductivity values were considered from the representative values of hydraulic conductivity for various geological formations (Domenico and Schwartz, 1990) as mentioned in Table 1.

Table 1. Rainfall Infiltration Factor and Hydraulic Conductivity Values

Sl. No.	Geological Units	Type	Recharge Rate* (m/day)	Hydraulic Conductivity Values (m/day)
1	Migmatites and Granodiorite - Tonalitic Gneiss	Fractured igneous and metamorphic rock	10% to 15%	0.0006912 – 25.92
2	Charnockite	Weathered granite	10% to 15%	0.28512 – 4.4928

*Recharge Rate = Percentage of normal rainfall in the area (GEC guidelines)

Riverbed Conductance

Riverbed conductance per unit meter length (m^2/day/m) were determined for different river segments (refer Fig. 4) of the Gowri hole using Eq. 1. Width (W) of different segments of Gowri hole was measured by using Google Earth. The hydraulic conductance of the river bed material, (K) for fine loamy sand was considered to be 2.5 m/day (Todd and Mays, 2005). The flow exchange between river and aquifer mainly depends on river stage and groundwater level as well as thickness of riverbed (Haque et al., 2012). Since the sub-surface exploration data was unavailable, the thickness of the riverbed (B) was assumed as 1 m.

Groundwater Draft

Figure 4 presents the village-wise distributions of dug wells considered for the study. Groundwater draft for the dug wells was determined using Water Power equation based on the statistical data disseminated by the Ministry of Water Resources, Government of India.

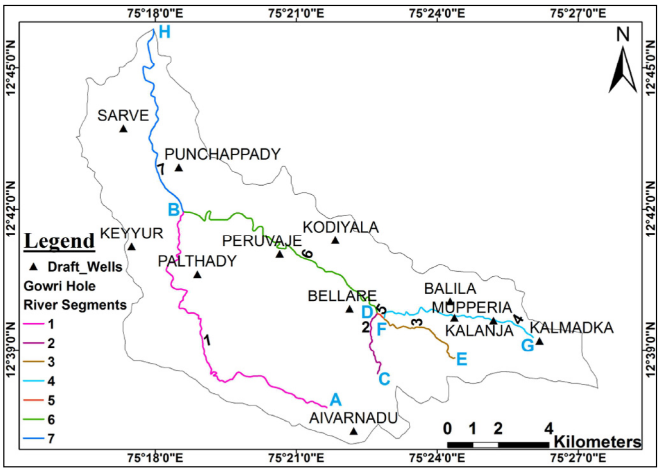

Fig.4. River Segments and Location of Dug wells.

Building the Conceptual Model

According to the conceptual modeling approach, different arcs and coverages were created from GIS layers imported into GMS. Hydro-geological data such as riverbed conductance values were assigned for river arc features. Aquifer properties such as recharge rate and hydraulic conductivity were defined for the recharge zones and layer aquifer boundaries respectively. Then, the conceptual model was converted into grid model for river-aquifer interaction simulations using MODFLOW.

Model Discretization

The study area was represented by a single-layered two-dimensional conceptual model grid consisting of 582 rows and 734 columns with 1,44,731 active cells. The size of each cell within the model domain was of approximate dimension 30 m x 30 m. Fig. 5 represents the DEM data that was interpolated into the top elevation values of the single-layered conceptual model grid. The bottom elevation value for the model layer was considered as -30 m.

Initial and Boundary Conditions

Fig. 5 also presents the model domain exhibiting the MODFLOW boundary conditions. The conceptual model was at first simulated under the steady-state condition for determining initial head conditions. Daily river-stage values and groundwater draft values were assigned for river arc features and wells respectively.

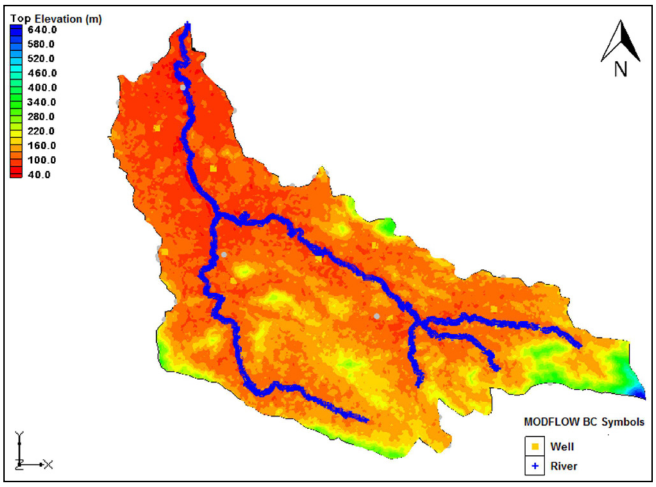

Fig. 5. DEM data with Boundary Conditions.

Model Calibration and Validation

Model calibration is often essential to estimate the aquifer flow characteristics. In the present study, the model was calibrated for transient analysis from June 2004 to May 2010 with a daily step input of all necessary hydro-geological data. Monthly observed groundwater head data available from two observation wells of Department of Mines and Geology and seasonal data of one observation well of CGWB were used for comparison of simulated and observed groundwater heads. During the calibration process, aquifer parameters such as hydraulic conductivity and recharge rate values were adjusted until computed and observed groundwater heads matched. The calibrated value of recharge rate was found to be 12.5 % of normal rainfall (rainfall infiltration factor). Also, the calibrated values for hydraulic conductivity were found to be 12.96 m/day for Gneiss and 2.39 m/day for Charnockite. Automated Parameter Estimation (Automated PEST) analysis was carried out to reduce the error in the calibrated model and to get better results from the study. The calibrated model was validated from June 2010 to October 2012 for two monthly observation wells of Department of Mines and Geology and one seasonal observation well of CGWB.

The calibration statistics of observed and computed groundwater heads of the simulated model are presented in Table 2. The statistics of the observation wells shows that the percentage difference in mean and standard deviation values are within the permissible limits. Similar trend was observed for datasets even during the validation period and hence the calibration of the flow model is justified.

Table 2. Calibration Statistics

Well Locations	Head values in metres above mean sea level	Minimum	Maximum	Mean	Standard Deviation
Madavu	Observed GW Heads	78.37	84.91	81.33	1.20
	Computed GW Heads	80.78	83.28	81.45	0.74
	Percentage Difference	3.07	-1.92	0.16	-
Bellare	Observed GW Heads	90.25	99.02	94.34	2.35
	Computed GW Heads	91.96	100.01	94.15	2.39
	Percentage Difference	1.89	1.00	-0.20	-
Sarve	Observed GW Heads	61.45	69.55	65.53	2.05
	Computed GW Heads	63.31	70.79	66.10	1.45
	Percentage Difference	3.03	1.78	0.87	-

Mean absolute error (MAE) for the simulated model was found to be 1.37 m and 1.28 m during calibration and validation period respectively. Root Mean Square Error (RMSE) was noted to be 1.79 m and 1.53 m for the calibration and validation period respectively. From the error summary, it can be concluded that errors of the simulated model in both the calibration and validation period are within acceptable limits.

RESULTS AND DISCUSSION

Temporal Variation of River Leakage and Aquifer Discharge

Figure 6 shows the time series representation of flow budget results of the simulated model for calibration and validation period. According to the conceptual modeling approach, rainfall recharge and river leakage are the volumes flowing inside the system whereas groundwater draft and aquifer discharge are the volumes flowing outside the system. The temporal variation of the river leakage and aquifer discharge in the study area is studied with respect to the total volume of flow inside and outside the system from Fig. 6.

During the calibration period, in the initial monsoon months from June to July 2007, river leakage reduced from 98,670 m^3 (10.2%) to 56,932 m^3 (3.6%), since high-intensity rainfall converted into runoff due to early saturation of the water-bearing units. The decline in peak rainfall from August provided enough opportunity for flow over the riverbed to recharge the aquifer beneath. Hence, river leakage significantly increased from 1,01,357 m^3 (10.8%) in September to 2,96,989 m^3 (50%) in December. Consequently, groundwater resources were much utilized in the area for irrigational activities during the post-monsoon period. From winter, river leakage sustained to occur

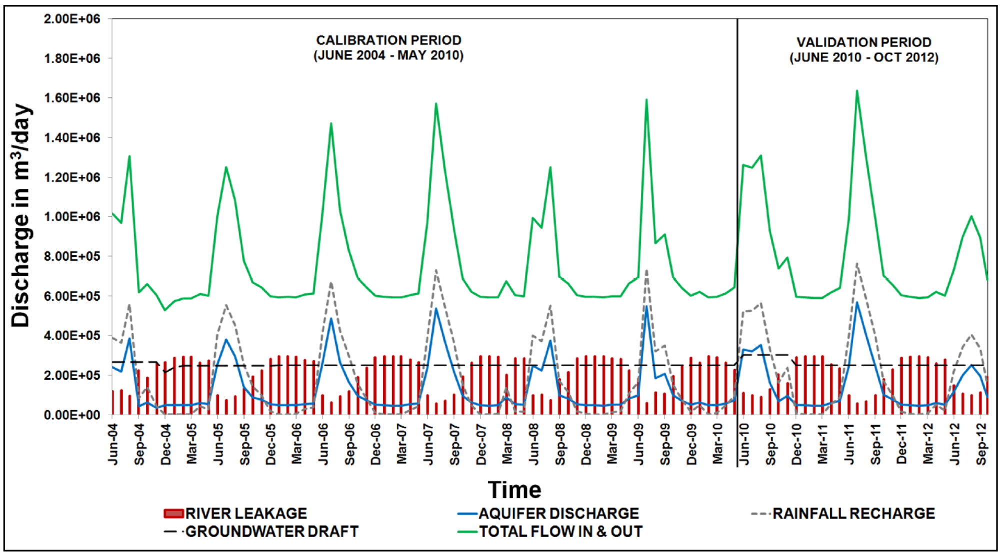

Fig. 6. Temporal variation of river leakage and aquifer discharge

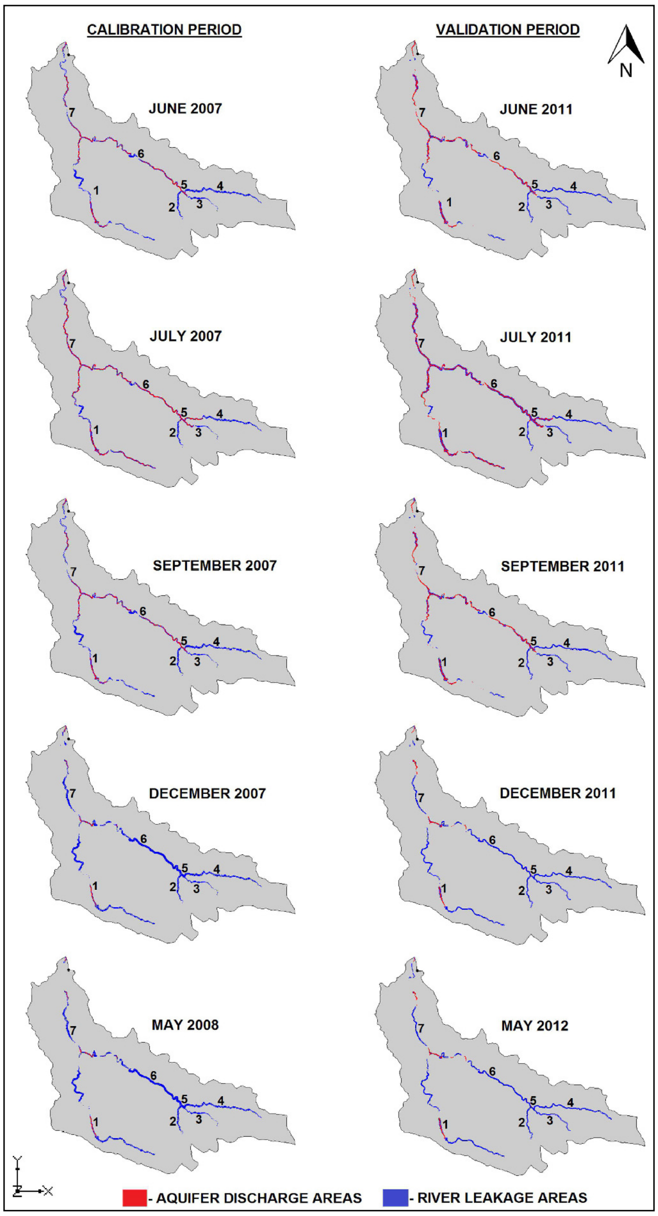

Fig. 7. Spatial variation of river leakage and aquifer discharge

even during summer months up to 2,84,811 m^3 (47.7%) in May 2008. With the increase in groundwater heads by the advent of monsoons in June 2007, aquifer discharge into the river flow increased from 2,35,070 m^3 (24.2%) in June to 5,36,910 m^3 (34.1%) in July. In the post-monsoon period due to the drop in groundwater heads, aquifer contribution into the river flow considerably decreased up to 46,710 m^3 (7.9%) in February 2008. Aquifer discharge continued till the summer period up to 49,213 m^3 (8.2%) until the end of May 2008.

For the validation period, in the year 2011, river leakage reduced from 98,711 m^3 (10%) to 54,661 m^3 (3.3%) from June to July. It drastically increased from 96,553 m^3 (9.8%) in September to 2,87,783 m^3 (47.8%) in December. River leakage slowly decreased to 2,80,380 m^3 (46.7%) in May 2012. River leakage found to be slightly under-estimated during post-monsoon and summer months. Aquifer discharge into the river flow increased from 2,43,500 m^3 (24.7%) in June 2011 to 5,67,883 m^3 (34.7%) in July 2011. In the post-monsoon, aquifer discharge noticeably decreased to 47,270 m^3 (7.96%) in February 2012, but existed to contribute up to 50,316 m^3 (8.4%) in May 2012. The dynamics in temporal variation of interaction during the validation period June 2011 – May 2012 proved to match with that of the calibration period June 2007 – May 2008.

Spatial Variation of River Leakage and Aquifer Discharge

The spatial variation of river leakage and aquifer discharge (m^3/day) over the study area for the calibration period and validation period is presented in Fig. 7.

From the study, the contribution of aquifer discharge into the river flow was consistent at the confluence point "B" (see Fig. 4) throughout the year. Some parts of river segments 1, 6 and 7 (see Fig. 4) of the study area were noticed to be under the influence of aquifer discharge. River segments 2, 3 and 4 (see Fig. 4) were dominated by river leakage areas. During peak monsoon months of June to July 2007, aquifer discharge areas appeared to majorly extend into the river segments 1, 5, 6 and 7 (see Fig. 4) due to augmented groundwater table caused by quick saturation. Whereas, river leakage areas were noticed in the river segments 2, 3 and 4 (see Fig. 4). From September to December 2007, river segments under the influence of aquifer discharge decreased due to the lowered groundwater table by the descent of peak monsoon flows. In this duration, it was observed that river leakage areas significantly increased until existent monsoon flows in the river diminished by the end of December. From January 2008, the dominant river leakage areas resulted in fragmentation and drying of some parts of river segments 1, 6 and 7 (see Fig. 4). Aquifer contribution areas sustained the low flow river segments from drying during summer months. For the validation period June 2011 to May 2012, the dynamics in the spatial pattern of interaction proved to match with that of the calibration period June 2007 to May 2008.

Quantification of River-aquifer Fluxes

The paper also focuses on the quantification of river leakage and aquifer discharge values (m^3/day) over the considered time for the Gowri hole sub-catchment. In the present study, river-aquifer fluxes

Table 3. River leakage and aquifer discharge values for different river segments in m^3/day

Time	River Segments						
	1 (AB)	2 (CD)	3 (EF)	4 (GF)	5 (DF)	6 (BD)	7 (BH)
June 2007	-57294.2	12853.0	8598.3	34927.4	-8354.9	-83054.9	-44074.6
July 2007	-153027.7	10074.0	-9193.6	638.7	-15349.7	-210308.1	-102811.8
Aug 2007	-104963.8	11641.9	-31.3	20816.5	-12653.4	-149745.3	-61123.1
Sep 2007	-53507.8	12856.9	8444.1	34797.3	-8411.5	-79807.4	-34921.2
Oct 2007	9012.5	13752.5	12564.5	38149.0	5530.5	34469.5	-15984.3
Nov 2007	33481.3	13766.3	12564.5	38149.0	5724.5	93027.4	5756.7
Dec 2007	44360.6	13766.3	12564.5	38149.0	5724.5	117833.3	16930.6
Jan 2008	44440.3	13766.3	12564.5	38149.0	5724.5	117964.2	16720.2
Feb 2008	44354.2	13766.3	12564.5	38149.0	5724.5	116828.2	15649.3
March 2008	7705.7	13766.3	12564.5	38149.0	5678.8	37442.2	-2073.1
April 2008	40542.9	13766.3	12564.5	38149.0	5724.5	108321.8	13604.2
May 2008	42093.3	13766.3	12564.5	38149.0	5724.5	108164.9	15135.3

were obtained from the computed flow of the river and stream arc features simulated by RIVER package using the conceptual modeling approach. Table 3 presents the flow exchanging between the river and aquifer in different river segments (see Fig. 4) from June 2007 to May 2008. The volumetric transformation of the river leakage denoted by positive values and aquifer discharge denoted by negative values presented in Table 3 proved to be the substantial evidence for the river-aquifer interaction.

CONCLUSION

From this study it was observed that Gowri hole acts as a gaining river during the monsoon due to aquifer discharge. It acts as a losing river due to river leakage during post-monsoon and summer months of the year 2008.

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