

River Aquifer Interaction in Lower Gandak Command Area in Bihar, India

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Abstract. In this paper, the quantification of the interaction of aquifer and river during various stages of river Gandak has been carried out. A groundwater flow model, MODFLOW, has been used to quantify the interaction of river Gandak and the adjacent aquifer in all months of the year. The model has been calibrated with the observed water level data of the existing wells. Calibrated model was used to simulate the groundwater flow in the study area and the flows from river Gandak to adjacent aquifer and vice-versa. Results show that the river Gandak is recharging adjacent aquifer during the months May to October and again during January to February. In the months March, April, November and December aquifer is contributing water to Gandak River. It was found that the quantity of inflow/outflow from river Gandak is proportional to the difference of water level in river and aquifer. Further, a relationship for the interaction of Gandak River and adjacent aquifer has also been developed to find the aquifer recharge with rise in river stage in the study area.

1. Introduction

Multilayered aquifers occur in a sedimentary groundwater basin which is separated by confining layers. These confining layers have very less permeability. Aquifer-stream interaction occurs at multiple scales in both time and space. A solution for river aquifer interactions problems is important as groundwater and surface water are not independent resources [1]. A river in such basin may be penetrating either partially or fully in the upper aquifer. The river stage varies from month to month. In monsoon, the stage of the river is high and in non-monsoon months the river stage goes down. The rise in river stages above the aquifer water table in the vicinity of the river leads to induced recharge to groundwater. Due to rise in river stage, the upper aquifer is recharged directly through the bed and banks of the river and the lower aquifers are recharged from the top aquifer through the intervening aquitard. In the process of interaction either water flow from aquifer to river or from river to aquifer. Recharge takes place if water level in a river is above the water table in the aquifer having permeable or semi-permeable material. This type of groundwater recharge may be temporary, seasonal, continuous, natural or induced by man through groundwater extraction.

The recharge is proportional to the difference in the water level of river and aquifer. This proportionality constant is known as reach transmissivity. The reach transmissivity depends on the stream bed characteristics and the shape of the stream cross-section. River aquifer exchange also depends upon structural geology [2] and dynamics pressure waves [3]. The water level in the aquifer depends on all the withdrawal and recharges including recharge from river. Several studies have been



carried out on single river aquifer interaction problem analytically. Three different basic analytical solutions currently exist for flow besides stream. First solution is based on the assumption that the stream and aquifer are perfectly connected, second solution is on the assumption that there is a vertical semi permeable boundary between aquifer and stream bank. Riverbed and bank permeability are determined by laboratories and field modelling. Third assumption is that stream slightly penetrates top layer of the aquifer and there is a semi permeable bottom of negligible width, and aquifer is extended to infinity in all direction horizontally [4]. However, accuracy of the flow calculation by application of classical horizontal flow model is checked by [5] and found that the velocity approach model is more accurate. For a partially penetrating river the exchange flow rates are reduced significantly in comparison to fully penetrating rivers. Interaction relationship for aquifer and the river is generally linear, however different for different morphology of river [6]. With the advancement in computational resources numerical methods have increased. Diffusion equation with sources and sinks terms solved numerically to obtain the interactions between groundwater and surface water [7]. Several studies have been carried out for the interaction of river and aquifer ([8]-[11]). [12] Produced an over view of the methods that are currently applied for river aquifer studies.

In this study, interaction of River Gandak and adjacent aquifer has been carried out during various stages of river in different months of the year. A groundwater flow model, MODFLOW under transient state has been used. [13] Examined the accuracy of simulation through MODFLOW for connected and disconnected losing stream. The model has been used to compute flow to/from Gandak River to adjacent aquifer at different locations along the river. River aquifer interaction relationship has also been developed to find the recharge with rise in river stage.

2. Study Area

Study area lies in lower Gandak basin in Vaishali and Muzaffarpur districts of Bihar, India having $84^{\circ}57'$ to $85^{\circ}08'$ E longitudes and $25^{\circ}56'$ to $26^{\circ}05'$ N latitudes. It is bounded by River Gandak in the western and Vaishali Branch Canal (VBC) in eastern sides. Habibpur sub-distributory (HSD) takes off at 138.2 RD of Vaishali Branch Canal and flows in the middle of the study area as shown in Figure 1(a) and the discretized image is shown in Figure 1b. River stage measurements were taken on the left bank of River Gandak at locations A, B, C, D, E, F, G and H as shown in Figure 1(b). The area comprises of an extensive plain formed by the alluvium brought by the river Gandak. It is mostly plain although few shallow depressions called 'Chauras' in local language are present. Estimated area is 181.6 km^2 . The elevation of the ground varies from 56.27 m to 50.90 m above MSL. The river Gandak forming western boundary of the study area is perennial in nature flowing towards south eastern direction. The average bed slope of river varies from 1:15000 to 1:20000. Stage data of river Gandak is measured at Rewaghat and Lalganj gauging sites which come in the study area.

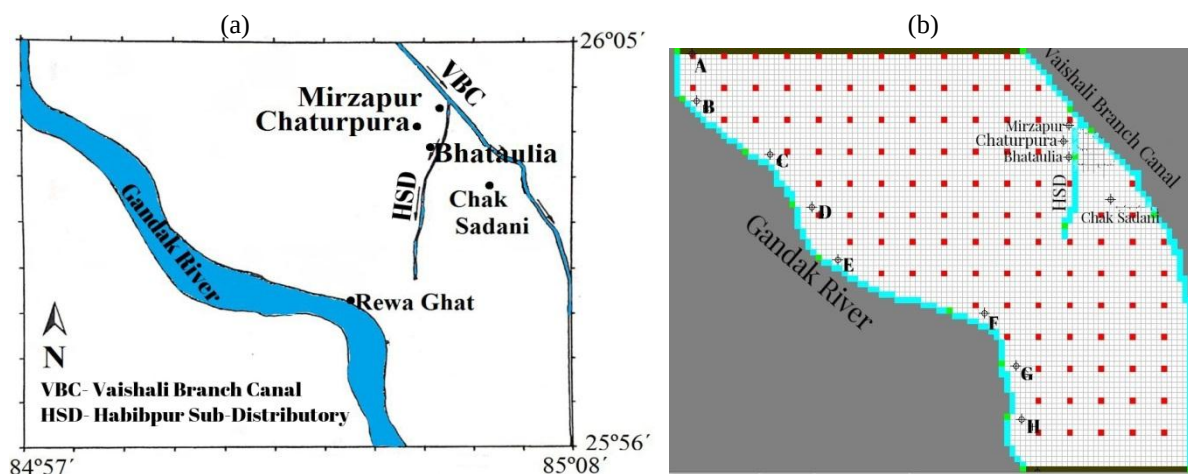


Figure 1. (a) Map of Study Area (b) Discretized image of study area.

Tirhut main canal is one of the three main canals receive water from Gandak main barrage at Balmikinagar. VBC takes off from Tirhut Main Canal at 554 RD (Reduced Distance = 1000 feet)

forming eastern boundary of the study area. It is an unlined canal having an average bed slope of 1:7000 with side slopes 1:1.5. The bottom width of canal is 17.5m. HSD provides irrigation facility through 18 outlets of 0.25 cumec average discharge each. There are 5 state tube wells and more than 900 private tube wells in the command area. The subsurface formations a thick pile of unconsolidated alluvial sediments having different texture, along with their admixtures. The study area lies in monsoon sub-tropical zone. The average annual precipitation is 1046 mm [14].

3. Methodology

Three dimensional groundwater flow model, MODFLOW [15] has been used in this study. MODFLOW consist various modules and module 'River Package' is used to simulate interactions of river and groundwater. Details of the MODFLOW are not presented here as it is well known and generally used model to simulate the groundwater flow.

3.1. Model Formulation

This area has been discretized into 100 columns and 80 rows comprising of 8000 cells of dimension 200×200 m and three layers of average thicknesses 15 m, 15 m, and 50 m. The values of parameters like hydraulic conductivity (K) and specific storage (S_s), and porosity for different layers has been estimated by Pump test done in year 1993. Transmissibility, $T = 400\text{--}700 \text{ m}^2/\text{day}$, Specific yield = 12–20% and Coefficient of storage = 0.015 have been taken from 'Vaishali district report' [16]. Water table elevation in the month of May, 1993 has been taken as initial condition. For convenience, all water table data have been raised by 100 m above MSL. West and east boundary of the study area is formed by Gandak river and VBC respectively whereas north and south boundary is open boundary termed as General Head Boundary (GHB). Wells and evapotranspiration have been considered as discharge component. According to census of Bihar, 957 shallow private tube wells were present in the study area. In modeling, 800 tube wells are distributed in first and third layer with discharge = $25 \text{ m}^3/\text{day}$. These wells are operational in Garma (summer) and Rabi crop seasons only. Monthly Evapotranspiration ET_o is taken at Patna and Muzaffarpur [17]. In cropped region, evapotranspiration is considered and in the region where crop is not grown only evaporation is considered. In the model, ET in non-cropped region is taken 50% of value that is in cropped region. Rainfall and irrigation return flows are considered as recharge. 20 % of the monthly rainfall has been considered as the recharge in the months of March to June and from November to February, whereas from July to October it is considered 70%. There are 18 outlets of the HSD. Each outlet has average discharge of 0.025 cumec irrigating approximately 10 ha of land. In model, 70% of discharge through outlet is taken as recharge. The canal is operational from July to October, January and 15 days in February in a year. Stream bed hydraulic conductance for Gandak river, VBC and HSD are $3000 \text{ m}^2/\text{day}$, $350 \text{ m}^2/\text{day}$ and $150 \text{ m}^2/\text{day}$ respectively.

3.2. Model Calibration

The results from model with reliable input parameters and stresses period generally come in close to observed field data. In case of mismatch either input parameters are unreliable or the stresses. If total number of operating wells in area is not known exactly, this cause underestimation of pumpage which further results overestimation of water table and vice versa. Similarly, for potential evapotranspiration value, [17] considered only solar radiation and ambient temperature as parameters. This may be a cause of not actual estimation of evapotranspiration. This will also be a cause of incorrect parameter resulting wrong estimation of water table. Thus, calibration of model parameter is required to check uncertainty part. In order to calibrate, model was simulated with the input values and stresses. The output water table elevation is then compared with observed water table elevation data of existing observation wells and according to mismatch, the parameters are modified. Calibrated values of different parameters hydraulic conductivity for all three layers are calibrated and presented in Table 1, whereas the calibrated rainfall recharge and evapotranspiration have been presented in Table 2.

One year daily observed water table data during 10.05.1991 to 12.05.1992 were available for four locations namely Mirzapur, Chaturpura, Bhataulia and Chak Sadani (Figure 1b). In addition to these, nine wells are assumed adjacent to river Gandak whose water table is taken same as stage of the river.

The observed water table elevation is compared with the computed water table of the calibrated model. Figure 2 present the comparison of observed and computed water table after calibration. In this figure, all the data have been plotted on a straight line at 45° to show the match between the observed and computed results. It is found that computed values of water table data are well matched with that of observed water table data. Thus, the process of calibration is terminated at this stage, and the model is ready for simulation.

Table 1. Calibrated values of Hydraulic Conductivity

Layers	Hydraulic conductivity (m/day)	
	Initial Value	Calibrated value
Layer 1	10	5
Layer 2	1	1
Layer 3	25	20

Table 2. Calibrated values of Rainfall Recharge and Evapotranspiration

Stress periods	Rainfall Recharge		Evapotranspiration			
	Initial Values (mm/day)	Calibrated values (mm/day)	Initial value (mm/day)		Calibrated value (mm/day)	
			Cropped area	Uncropped area	Cropped area	Uncropped area
Mar	0.06	0.03	3.94	1.97	6.32	4.15
Apr	0.05	0.03	4.85	2.43	8.73	3.88
May	0.18	0.18	8.09	4.05	8.09	4.04
Jun	1.01	1.01	6.34	3.17	5.07	2.53
Jul	5.95	5.95	1.84	0.92	0.83	0.27
Aug	6.42	6.42	3.26	1.63	3.26	0.63
Sep	4.68	4.68	5.93	2.96	5.93	1.96
Oct	1.17	1.17	5.40	2.70	5.40	1.70
Nov	0.07	0.07	1.42	0.71	2.42	0.71
Dec	0.02	0.02	2.36	1.18	2.36	1.18
Jan	0.14	0.14	3.60	1.80	3.60	1.80
Feb	0.11	0.11	4.51	2.26	4.51	2.26

4. Results and Discussions

The ground water model has been developed and calibrated with the water table data at certain existing observation wells in the study area for all the months of the year. Calibrated model has been used to study the river aquifer interaction in the study area. For this purpose, nine different locations are selected based on the morphology of the river such as after the bends, in straight portions and near the bends. For instance, locations from the northern entry Point of Gandak River to the distance of 0.1, 4.4 and 7.2 km in downstream of the river are straight portion; at distance 2.0 and 19.4 km are after bends and locations at distances 9.2, 14.2, 17.2 and 21.4 km are near bends. In order to analyze the nature/direction of flow through Vaishali Branch Canal and Habibpur Sub-Distributory, five such more locations in Vaishali Branch canal and two in Habibpur Sub-Distributory are selected. Two series of simulations and analysis have been carried out in this study. In the first series of simulation, monthly analysis of inflow to and from aquifer at these locations has been carried out. Positive value of flow shows that water is flowing from river to the aquifer and negative value means flow is from aquifer to the river. Second analysis is the effect of incremental rise of river stage on the river aquifer interaction and a relationship has also been developed for this. Figures 3(a-c) present the nature/direction and magnitude of the flow between River Gandak and aquifer at different selected

locations for all the months. Figure 3(a) shows results at distances 0.1, 2.0 and 4.4 km from the entry point of river Gandak. Similarly Figures 3(b) and 3(c) shows the interaction at the distance 7.2, 9.2 and 14.2 km and 17.2, 19.4 and 21.4 km, respectively along the river Gandak. Positive value of flow shows that water is going from river to the aquifer and negative value means flow is from aquifer to the river.

From figures it can be seen that aquifer is contributing water to river in almost all the months except May, June and July. Nature of flow at all the reaches of river is same but there is variation in magnitude.

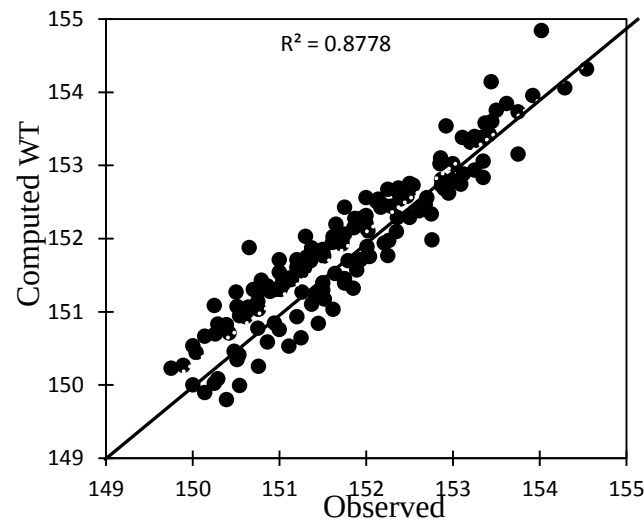


Figure 2. Comparison of observed and computed water table after calibration of model.

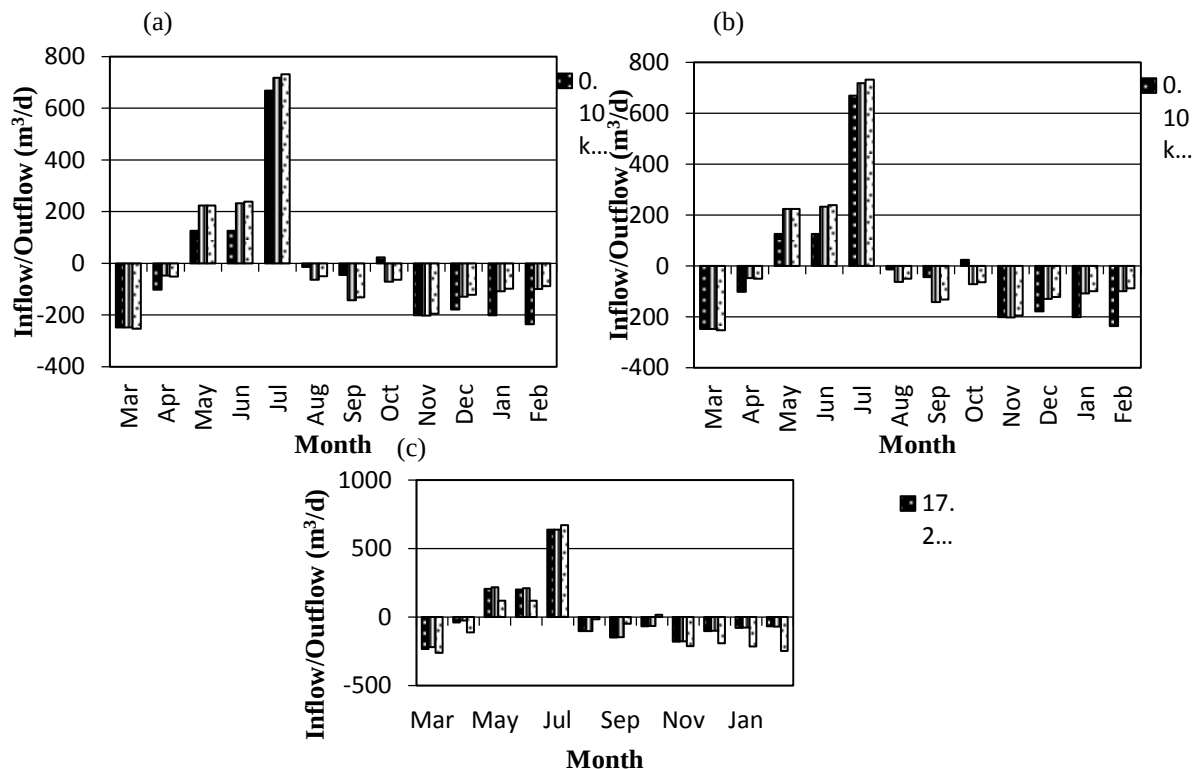


Figure 3. Inflow/Outflow to Aquifer at distances (a) 0.1, 2.0 and 4.4 kms (b) 7.2, 9.2 and 14.2 kms (c) 17.2, 19.4 and 21.4 kms from river Gandak.

Figures 4(a, b) show the nature of flow between VBC, HSD and aquifer. These figures show that VBC and HSD always contributing water to aquifer when these are operational. Figure 5 shows the nature and quantity of flow between aquifer of command area and River Gandak, VBC and HSD taken as a whole. It is found that the flow is from river to aquifer during the months May to October and in January and February with maximum quantity of flow is in the month of July. In the remaining months direction of flow is from aquifer to river with maximum value in month of March. Morphology of the river, water table condition and other stresses may be the reason to these variations in relations.

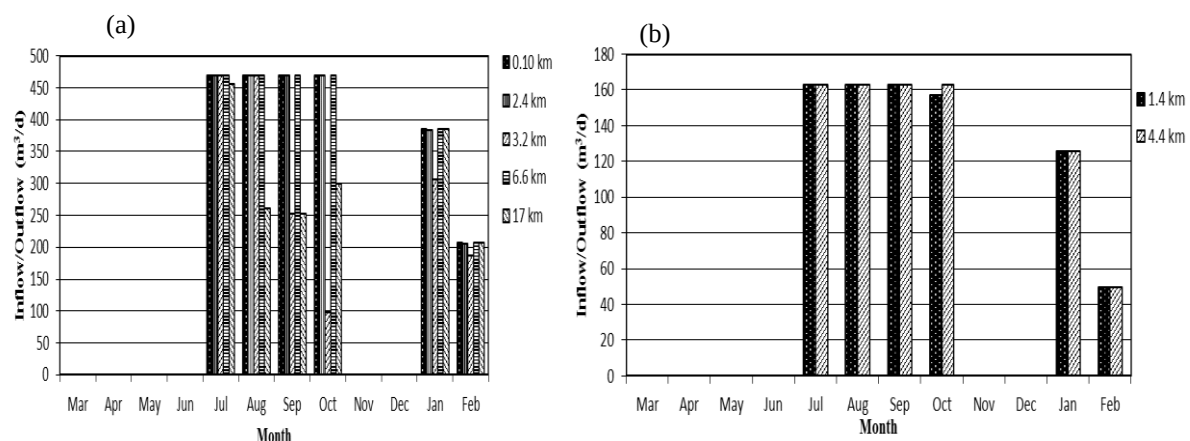


Figure 4. Inflow/Outflow to Aquifer at (a) 0.1, 2.4, 3.2, 6.6 and 17.0 kms from VBC (b) at 1.4 and 4.4 kms from HSD.

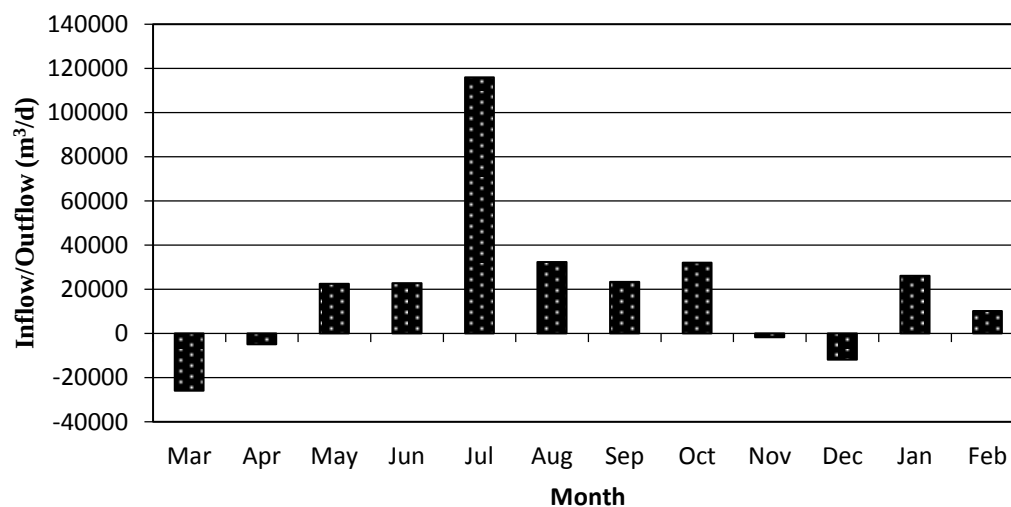


Figure 5. Inflow/Outflow to Aquifer from whole Gandak command area.

For second series of simulation, discharge is noted at each location after every unit increase of river stage. This incremental rise in stage versus discharge gives us a linear relationship. A generalized relation for whole study area is obtained which gives quantum of discharge between river and adjacent aquifer. The obtained linear equation is $y=14986x-2^6$, shown in Figure 6.

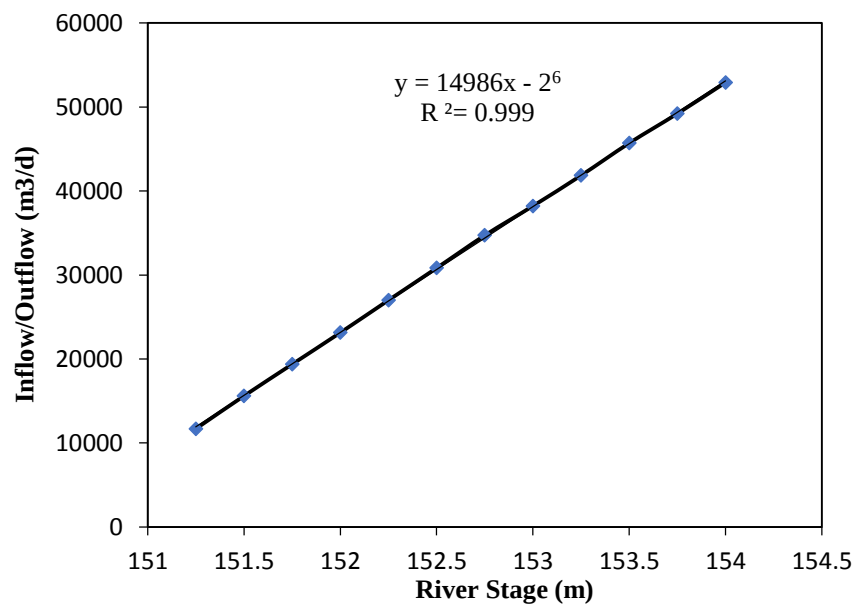


Figure 6. River aquifer interaction relationship for Gandak command area.

5. Conclusions

River aquifer interaction in the command area of Gandak in Bihar, India has been simulated using module 'Rivar Package' of ground water model, MODFLOW. Model has been developed and calibrated with the water table data at certain existing observation wells in the study area for all the months of the year. Calibrated model has been used to simulate the groundwater flow for one complete year. Results obtained as the water level data at all the grids and in term of the flow direction and magnitude either from river Gandak to adjacent aquifer or vice-versa. It is found that the flow is from river to aquifer during the months May to October and in January and February with maximum quantity of flow is in the month of July. In the remaining months direction of flow is from aquifer to river with maximum value in month of March. This shows that flow of water between Gandak and the aquifer depends upon stage of river, morphology of the river, and water table condition in the aquifer adjacent to river. The relationship of river aquifer interaction is linear in general and different for different reaches. River aquifer interaction relationship ($y = 14986x - 2^6$) developed for incremental rise in river stage gives the quantity of flow due to stage of river in study area as a whole.

6. References

- [1] Mishra G C and Fahimuddin M, 2005 'Stream Multiaquifer Well Interactions', Journal of Irrigation and Drainage Engineering, Vol. 131, No. 5: pp 433-439.
- [2] Fleckenstien J H, Niswonger R G and Fogg G E, 2006 River-Aquifer Interactions, Geological Heterogeneity and Low-Flow Management. Vol.44, No.6- Groundwater- November- December 2006, p-837-852.
- [3] Calderon H and Uhlenbrook S 2014 Investigation of seasonal river- aquifer interactions in a tropical coastal area controlled by tidal sand ridges. Hydrology and Earth System Sciences. Discussion. 11, pp 9759-9790.
- [4] Hunt B, Weir J and Clausen B, 2001 A stream depletion field experiment. Ground Water 39(2) pp 283-289.
- [5] Nawalany M and Grodzka M, 2014 'River- aquifer interaction- analytical solution for groundwater horizontal flow model vs. velocity oriented approach in 3D'. Revista Latino-Americana de Hidrogeologia, vol. 9, No. 1, pp. 131-136.
- [6] Chakraborty B and Pandey N G, 2004 Flood and its effect on River Aquifer Interaction.
- [7] Anderson M P and Woessner W W, 2002 Applied groundwater modeling: simulation of flow and advective transport. Academic Press, London.

- [8] Constantz J, 2008 Heat as a tracer to determine streambed water exchanges, *Water Resour. Res.*, 44, W00D10.
- [9] Ruehl C, Fisher A T, Hatch C, Huertos M L, Stemler G and Shennan C, 2006 Differential gauging and tracer tests resolve seepage fluxes in a strongly-losing stream, *J. Hydrol.*, 330(1-2), pp 235–248.
- [10] Hatch C E, Fisher A T, Revenaugh J S, Constantz J and Ruehl C, 2006 Quantifying surface water-groundwater interactions using time series analysis of streambed thermal records: Method development, *Water Resour. Res.*, 42, W10410.
- [11] McCallum A M, Anderson M S, Rau G C, Larsen J R and Acworth R L, 2014 ‘River-aquifer interactions in a semiarid environment investigated using point and reach measurements. *Water Resour. Res.*, 50, pp 2815–2829.
- [12] Kalbus E, Reinstorf F and Schirmer M, 2006 Measuring methods for ground water and surface water interactions: a review. *Hydrology and Earth System Sciences Discussions*, European Geosciences Union, 2006, 10 (6), pp 873-887.
- [13] Brunner P, Simmons C T, Cook P G and Therrien R, 2010 Modelling Surface water Groundwater interaction with MODFLOW: Some considerations. *National Groundwater Association*. Vol.48, No.2- GROUND WATER- March-April 2010 pp 174-180.
- [14] Bihar Irrigation Commission Report (1994) Vol-II, pp 53-60.
- [15] Barlow P M and Harbough A, 2006 USGS directions in MODFLOW development. *Groundwater* 44(6) pp 771-774.
- [16] CGWB 1993 Hydrology and Groundwater resources of Vaishali district, Bihar Technical report no. 103, series ‘D’.
- [17] Hargreaves G N, Prasad U K and Sumani Z A 1985 Acrop water evaluation manual for India., The Irrigation centre, Utah State University, USA, pp 85-86.