

Chapter 9

Impact of Urbanization and River Morphology on Groundwater System in Patna Urban Area, Bihar, India



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Abstract The impact of increased groundwater demand due to vertical urban growth and a shift in the course of the river Ganges in the Patna urban area (PUA) has been analyzed through a numerical groundwater flow model in this chapter. The model simulation indicated a large cone of depression in the deeper aquifer in the central parts of PUA. The cone of depression of each tube well is interfering with each other. Depending on the pumping rate (2000–7000 m³/day) of the individual tube well, the radius of influence of wells is between 100 and 200 m. The hydraulic head of the deep aquifer in the central part of PUA has declined by 2 m (maximum) from 1990 to 2002, which has now declined to 4–6 m (maximum) in 20 years. The simulated results with the existing stress conditions on the aquifer system indicate that there is a 0.5 m/year decline in the hydraulic head of the deep aquifer in the central parts of PUA.

Keywords Groundwater · Groundwater flow model · Patna urban area

1 Introduction

Patna urban settlement is situated in a vast Indo-Gangetic plain and on the river Ganges bank (Figs. 9.1 and 9.2). Being on the bank of a huge perennial river, even then, the water supply to Patna Urban Area (PUA) is met solely from groundwater. It is mostly due to a cost-benefit analysis between surface and groundwater. The Patna Municipal Corporation (PMC), responsible for the drinking water supply, made 110 high-yielding deep tube wells in different localities within the PUA limit.

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Fig. 9.1 Google Map of the study area – an extent of model boundary for Patna urban

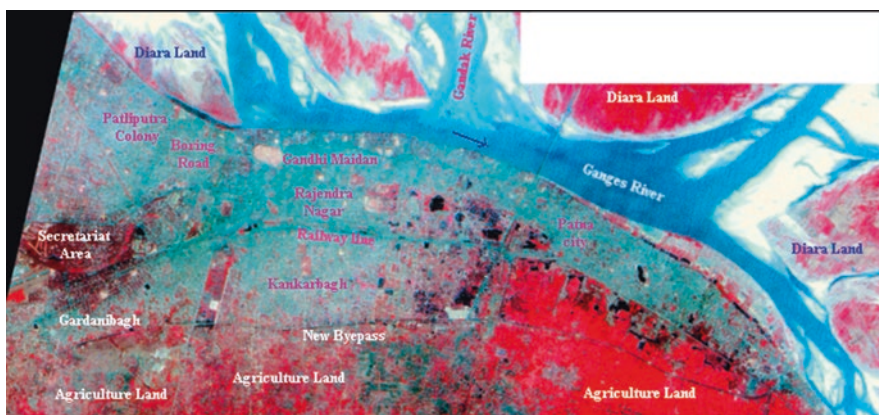


Fig. 9.2 IRS-1D satellite data of Patna urban area and river Ganges (2000)

These tube wells are in a depth range of 150–200 m below ground level. The pumping rate of these well is in between 4000 and 8000 m³/day, except a few are abstracting in between 3000 and 4000 m³/day. About 418,000 m³/day of water is required to provide drinking water to an estimated population of 2.48 million in the municipal area of the city. To meet the demand, the municipal corporation is approximately abstracting 698,000 m³/day of groundwater through 110 deep high-yielding tube wells in different municipal wards. In 2001, there were 77 operational tube wells, which could abstract a total of 141,000 m³/day of groundwater against a water demand of 215,240 m³/day (Table 9.1). Besides, individual residential houses and multistoried apartments are also abstracting groundwater from shallow as well as deep aquifers to meet the water demand for drinking and domestic water. This is additional unaccounted stress to the aquifer system. Patna urban development plan

Table 9.1 Patna urban water demand

Years	2001	2011	2021 (estimated)
Population (million)	1.43	1.73	2.48
Domestic water demand, including commercial/ institutional (m ³ /day)	183,700	221,100	372,230
Industrial demand (m ³ /day)	21,500	25,900	31,200
Floating population demand (m ³ /day)	10,000	12,100	14,641
Total demand (m ³ /day)	215,200	259,000	418,071
Designed water supplying capacity (m ³ /day)	153,700	96,000	205,000
Deficit (m ³ /day)	61,500	163,000	213,071

indicates there will be a need to construct additional 43 new tube wells to meet the projected urban population by 2038 (BRJP, 2003), apart from the existing 77 tube wells in 2001. To be more conservative in estimation, taking minimum efficiency of pumping tube wells, the annual withdrawal of groundwater comes to be 56.10×10^6 m³/year. There are approximately 1700 apartments in the PUA. Most of the apartments are operating a 5HP submersible pump, which pumps water at a rate of 200 m³/day. The total conservative withdrawal from the deep aquifer comes around 68.51×10^6 m³/year, which is higher than the annual replacement of the deep aquifer. So, it may be concluded that pumping is currently being done beyond the sustainable limit.

The hydraulic head of the deep aquifer has a declining trend, whereas the water table in the phreatic aquifer has an increasing trend in PUA (Maitra & Ghose, 1992; CGWB, 2000, 2007, 2015, 2016). The historical data on groundwater level indicates a 1 m decline in the hydraulic head of the deep aquifer between 1990 and 2000. The shallow low-yielding aquifer is already in stressful conditions, and now private tube wells are targeting the deep aquifer from where the municipal corporation is making bulk groundwater supply. This provides an opportunity to study the temporal and spatial behavior of aquifers with the projected groundwater abstraction. The aquifer geometry, dynamic and static storage, interconnection with other hydrological systems, and its spatial and temporal variation require to be understood for its sustainable utilization and development of a long-term management plan for the deep aquifer.

1.1 Study Area

Patna town is situated on the bank of the Ganga river, which is the largest river in India. The study area is the urban limit of Patna town, and this study considers a 210 km² geographical area. The study area is located between latitude 25°30'–25°40' and longitude 85°–85°20'. The old town is located along the natural levee of the river, whereas the new town is spread over the depressional area just after the natural

levee, which is mainly in the eastern part of the town (Fig. 9.2). In topographic elevation within PUA is varying between 45 and 60 m MSL. The western town is at higher elevation and traces of paleochannel of Son River have also been observed. In general, depressional area elevation is about 50–55 m MSL, whereas natural levee elevation ranges between 60 and 65 m MSL. The southwestern has a higher elevation, and the maximum elevation is within the 65 m MSL.

1.2 River Bank Morphology

There is a narrow linear stretch of natural levee that exists all along the river bank in the mid part to eastern part and followed by backside depression land (Fig. 9.3). Natural levee runs all along the river bank, with the eastern side being at a higher elevation which gradually merges with normal ground elevation in the western part. There is a sharp drop in elevation between the river bank and ground where the natural levee gradually ends on the western side and reaches normal ground elevation.

The change in elevation between ground and river bank is also gradual. The lateral flood plain of the river is very wide, and it is up 10 km, whereas the northern bank of the river is stable. The river main flow channel is very dynamic, and it changes every year during the flood period. The river reaches at the high stage during the monsoon period and remains at the lowest stage during summer. The river water level fluctuates between 42 m MSL to 48 m MSL. The flat and wide, low-lying flood plain of the river is likely to act as a recharge area for the shallow as well as deeper aquifers. The river main channel has a very significant role in controlling and inflow and outflow of the aquifer system near PAU. The shifting of the river channel away from the historical southern bank is likely to affect the groundwater sustainability of the aquifer system both in terms of availability and quality. In the

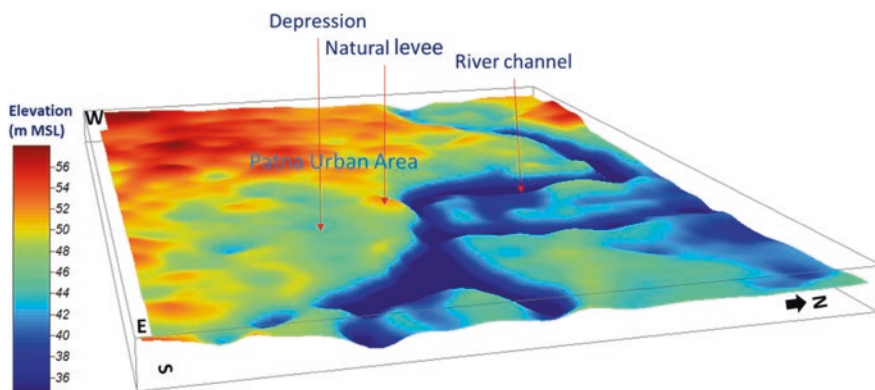


Fig. 9.3 Digital elevation model of landforms in Patna urban area along with the Ganga river

year 2000, the river’s main course was away from the historical river bank in the western part (Fig. 9.4), which gradually shifted further north in 2010 (Fig. 9.5). However, the river’s main course remained unchanged in the eastern parts. Now in the period of 2019–2021 the river main course will be reached closer to the historical river bank (Fig. 9.6). This dynamic behavior of the main river course, which is unpredictable has a direct impact on the groundwater system of PUA and creates uncertainty in the groundwater recharging capacity of the river.

1.3 Hydrogeology

The PUA is a part of the vast Gangetic plain. The alluvial deposit near Patna has been derived from the transportation of the Himalaya and Chota Nagpur Plateau sediments. The basement depth near Patna is more than 1000 m (Bose et al., 1966). Both the sediments have different hydro-geophysical characteristics (Ashok Kumar & Thambidurai, 2022). It has also been observed that the river Ganges was the dividing line for the sediments brought from the Chota Nagpur plateau and Himalaya. There is the presence of alternate layers of sand and clay (Fig. 9.7).

Broadly, three aquifers are packaged beneath the PUA (Fig. 9.7). The top aquifer is mainly a fluvial deposit dominated by clayey on the back side of the natural levee. The second aquifer, which dominantly consists of fine-grained sand, is beneath the first layer but has reached the ground surface on the western side. The thickness second aquifer is variable over the PUA. There is also a well-defined paleochannel of the river Son, which occupies comparatively high ground level and is a part of the second layer. However, its surface exposure is limited. This acts as a recharge area to the middle-level aquifer and, at the same time, due to its high transmissivity, may pose a risk for contaminant migration to the middle aquifer. The third aquifer is

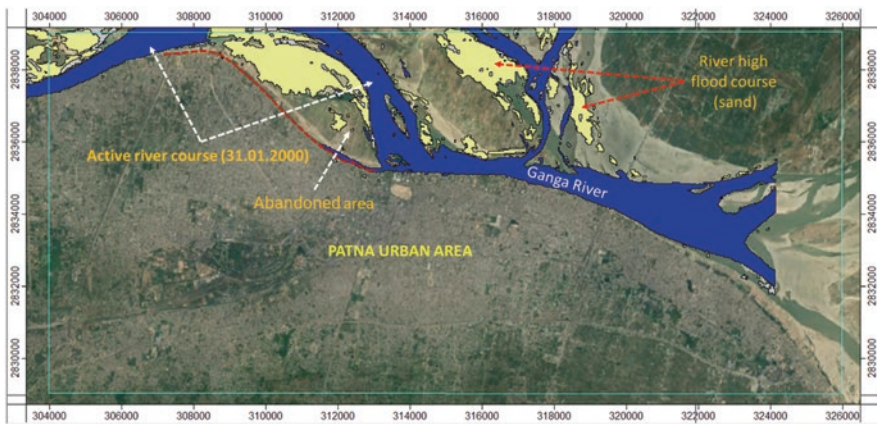


Fig. 9.4 Ganga river main course during January 2000 (lean period) based on satellite data

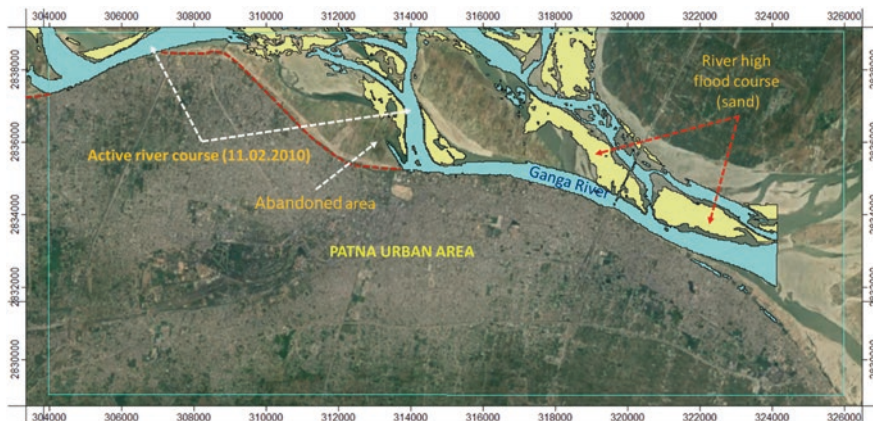


Fig. 9.5 Ganga river main course during February 2010 (lean period) based on satellite data

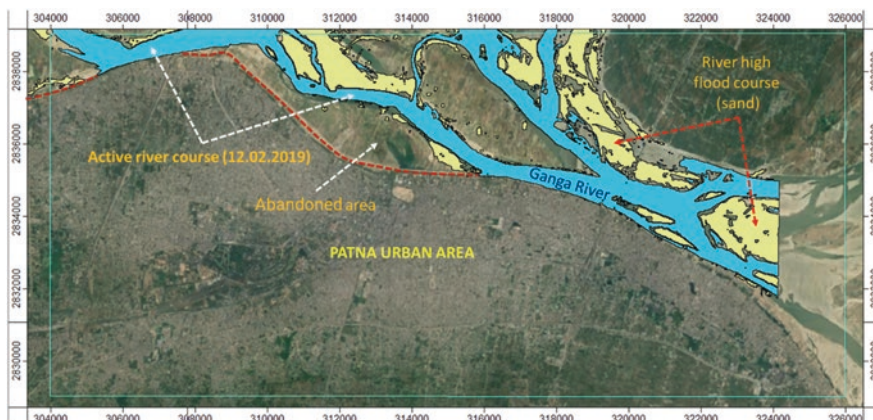


Fig. 9.6 Ganga river main course during February 2019 (lean period) based on satellite data

below the second aquifer, separated by a 30- to 50-m-thick clay layer. The upper portion of the third aquifer consists of medium sand and gradually changes to gravel and pebbles in depth. The third aquifer is very thick and widespread. This aquifer serves as the principal aquifer for the Patna urban water supply. The water table data for 1985 (Fig. 9.8) depicts regional groundwater flow patterns. But rapid urbanization after 1985 has resulted in a change in flow patterns. The water level of the unconfined aquifer has a rising trend (BRJP, 2003). This is mainly due to increased recharge from urban drainage and soaks pits. The hydraulic head of the deep aquifer has decreasing trend due to the high abstraction of urban water supply. The hydraulic head (Fig. 9.9) of the third aquifer varies between 41 and 45 m MSL. The higher head value is in the upper reaches compared to the head value near the river. In the

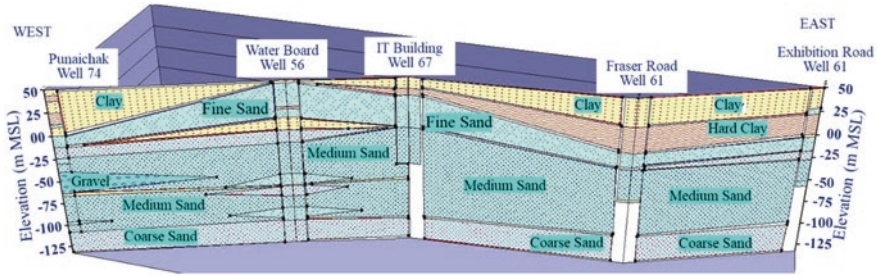


Fig. 9.7 Fence diagram of multilayer aquifer system in the urban area of Patna

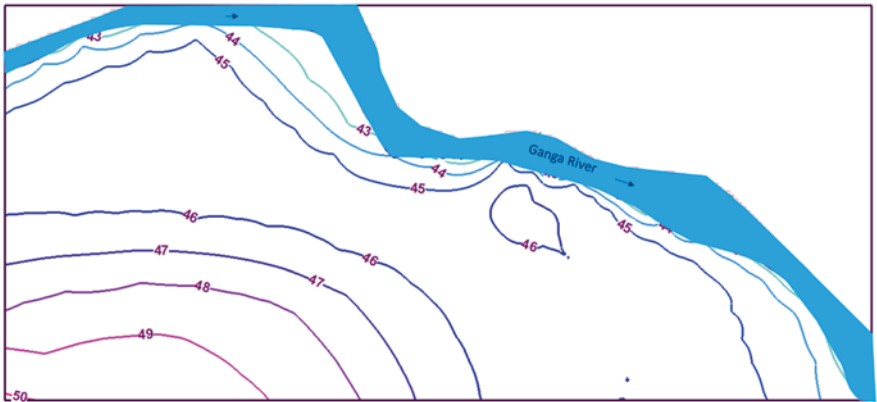


Fig. 9.8 Hydraulic head of unconfined aquifer (layer-1) in 1985

deep aquifer (third aquifer), the dominant flow direction of groundwater is from SW to NE direction.

The unconfined aquifer has been less explored in the earlier scientific study, and very limited data is available on aquifer parameters. The present study has been characterized based on available published information (Maitra & Ghose, 1992). The third aquifer (confined) has been explored in detail by the CGWB (1981, 1996, 2000). It has been observed that the transmissivity value of the aquifer varies from 3500 to 17,000 m³/day. The storage coefficient varies from 0.005 to 0.0001 (Table 9.2).

1.4 Groundwater Recharge Potential

Presently 210 km² area of PUA is under consideration, and the average annual rainfall is 996 mm in the area. However, the mid-eastern parts of PAU are dominated by a thick clayey layer, and it is expected that recharge to lower aquifer is likely to be



Fig. 9.9 Hydraulic head of confined aquifer (layer-4) in 1985

Table 9.2 Transmissivity of the deep aquifer (layer-4) at different location in PUA

Name	Transmissivity (m ³ /day)	Name	Transmissivity (m ³ /day)
Takiyapur, Danapur ^a	5775	Anisabad ^b	6621
Danapur ^a	15,984	Begampur ^b	3786
Raj bhawan ^a	6989	Chhajjubagh ^b	7114
Sanskrit Vidya Parishad ^a	3600	Congress maidan ^b	5892
CDA (MES), Kadamkuan ^a	4982	Goalghar ^b	14,113
P&T colony, Kidwaiपुर ^a	4908	Harding road ^b	6820
Bata shoe co., Digha ^a	4393	Karbigahiya ^b	8057
Press field, Gilzarbagh ^a	3529.9	Khagaul ^b	17,000
PESC Ltd., Mithapur ^a	8163	Khajekalan ^b	10,246
Chandmari road ^b	13,650	Phulwari Sharif ^b	7894
TW no.2, Kankarbagh ^b	5144	Sanatan dharamshala ^b	6980
Mangal Talab, Patna City ^b	7896	Digha ^b ***	7068
Phulwari changar ^b	2008.9	Malsalami ^b	12,235
Aalamganj ^b	9882	Harding park ^b	9924

Source: ^aMaitra & Ghose (1992), ^bBRJP (2003)

limited in this area, whereas the western parts have better groundwater recharge prospects both due to comparatively better hydraulic characteristics of the unconfined aquifer. The historical data has indicated that the average seasonal variation in the third (confined) aquifer is approximately 1.5 m in groundwater level. The recharge to the groundwater system has been estimated, assuming rainfall infiltration as 15% and specific yield as 0.10. The annual increment in groundwater has

been computed on the basis of seasonal variation of water level as well as rainfall infiltration factor. The annual groundwater increment on the basis of the rainfall infiltration method is $31.50 \times 10^6 \text{ m}^3/\text{year}$, whereas the methodology based on specific yield and seasonal rise in water is $78.50 \times 10^6 \text{ m}^3/\text{year}$. This difference between the two methodologies indicates that seasonal rise in water level of deep aquifers is not only governed by rainfall recharge from the top surface, but recharge from Ganga river and inflow from surrounding parts of the aquifer also contribute. This estimate requires a better understanding of the entire groundwater system in the PUA. The numerical groundwater model is one of the better tools to visualize the entire groundwater system and forecast the long-term behavior of the groundwater system with current and projected stresses to the entire groundwater system.

2 Numerical Groundwater Model

The numerical groundwater flow model has been developed using MODFLOW 2005 package with available data. The deep tube wells drilled by the BRJP (2003) has provided vital information about the aquifer property. Earlier studies carried out by Chatterjee and Garrett (1953), Nath (1981), Pandey et al. (1982), Maitra and Ghose (1992), Nath and Tripathy (1996), and BRJP (2003) have provided historical data. Data on temporal and spatial variations in the hydraulic head of the third aquifer was limited, and it has been generalized over a large area. Therefore, the developed groundwater model is based on various assumptions or generalizations. The model has been tested for 10 years by considering monthly stresses to the aquifers. This has been done mainly to observe the influence of the Ganga river stage on the aquifer behavior.

2.1 *Aquifer Geometry*

Based on the available lithologs, aquifer geometry has been conceptualized. It has been found that it is more appropriate to consider four layers aquifer system to reasonably apply the stresses to different layers (Figs. 9.10 and 9.11).

2.2 *Hydraulic Properties*

The lithological evidence indicates each layer is not completely isolated from the others. It has some interconnection between them in many places. Therefore, the hydraulic properties of each layer have been subdivided into different zones to take care of the spatial variation in aquifer property (Table 9.3).

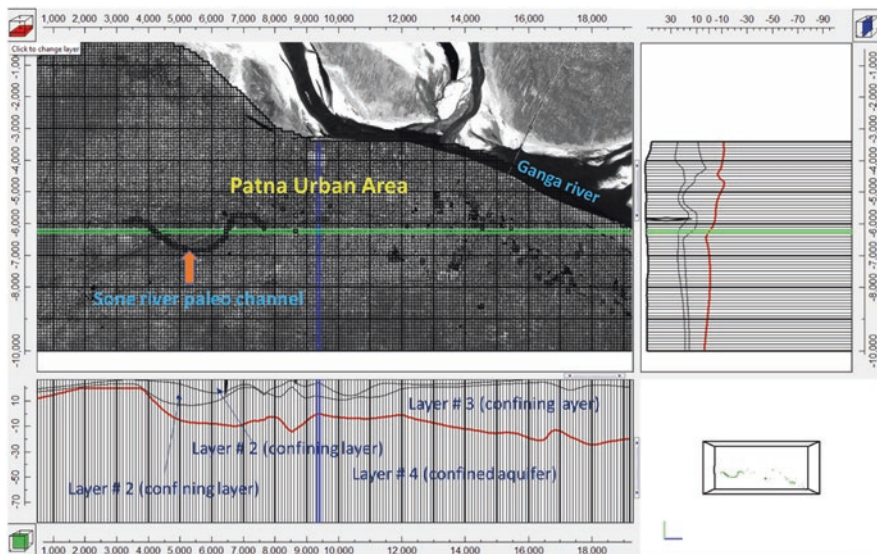


Fig. 9.10 Conceptual layer geometry within Patna urban settlement in modelling environment

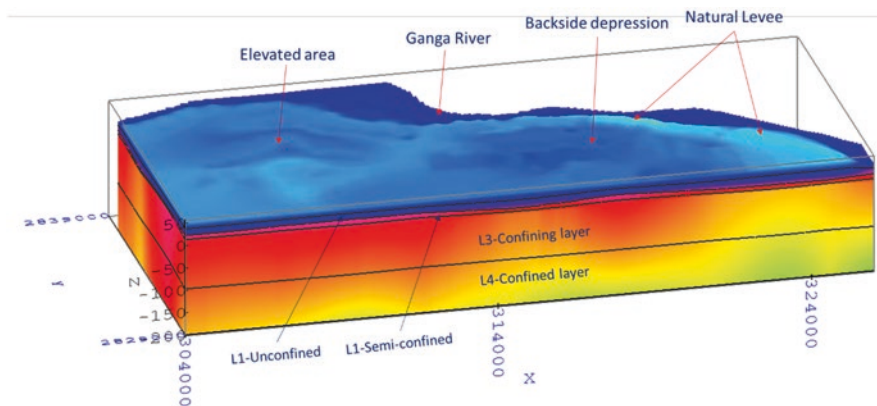


Fig. 9.11 3D visualization of layer geometry within Patna urban settlement in modelling environment

2.2.1 Initial Head

The initial head has been derived from the historical data and its trend. Based on the trend of the long-term hydraulic head of different layers, the historical water level of 1985 has been extrapolated up to 2003. The interpolated head has been further smoothed by running the model in steady state conditions (Figs. 9.12 and 9.13). The transient head of the middle aquifer (layer-2) and lower aquifer (layer-4) shows the cone of depressions in the pumping well area (Fig. 9.14). The historical data

Table 9.3 Model parameter for aquifer system of Patna urban area

	Layer-1	Layer-2	Layer-3	Layer-4
	Fine sand clay intermixed	Fine to coarse sand	Dominantly clay, fine to coarse sand	Coarse sand and gravel
Hydraulic conductivity (m/day)	0.1–1	–	–	–
Transmissivity (m ² /day)	–	6000	500–4000	8000
Primary storage coefficient	0.001–0.18	0.0025	0.001–0.00001	0.005
Aquifer porosity	0.18–0.20	0.27	0.1–0.21	0.25
River bed conductance (m ² /day)	10,000 (assumed on the basis of best fit case)			
Recharge (m/day)	0.0005			
Evapotranspiration (m/day)	0.0003			

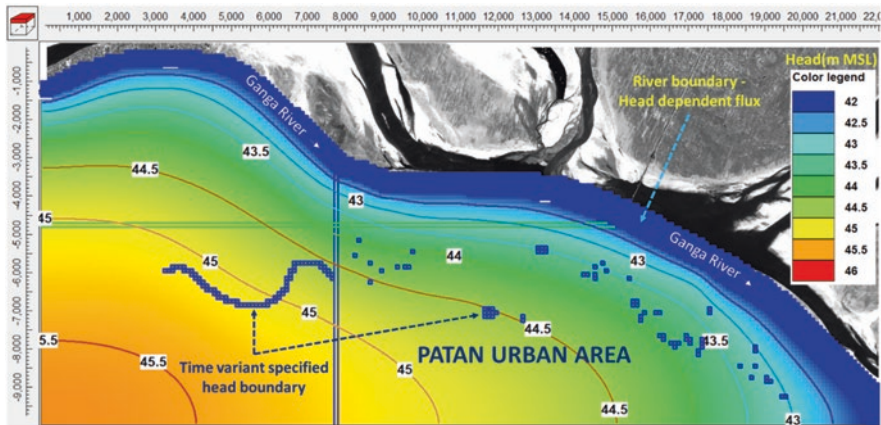


Fig. 9.12 Model of initial steady state hydraulic head (2003) of layer # 1 (unconfined aquifer)

indicates that the upper unconfined aquifer (layer-1) and deep confined aquifer (layer-4) have a different hydraulic head. The upper aquifer (layer-1) has a higher hydraulic head and is more uniform than the lower aquifer (layer-4). This is mainly due to the upper aquifer’s negligible utilization of the upper aquifer, whereas the lower confined aquifer is being heavily utilized for town water supply as well as for individual households for drinking and domestic water needs.

2.2.2 Model Boundary Conditions

The considerable part of the eastern side of PUA is located on the back side depression of the natural levee. Many permanent water bodies/waterlogged area exist. Similarly, a water-filled paleochannel of Son River is present. These water bodies

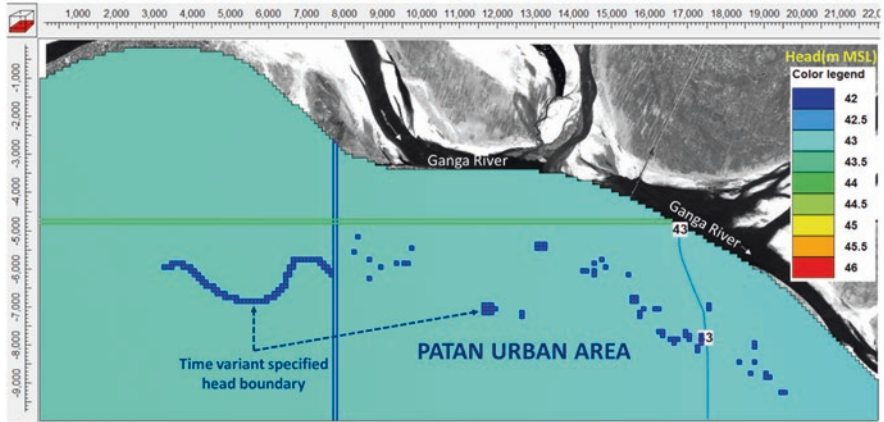


Fig. 9.13 Model of initial steady state hydraulic head (2003) of layer # 4 (confined aquifer)

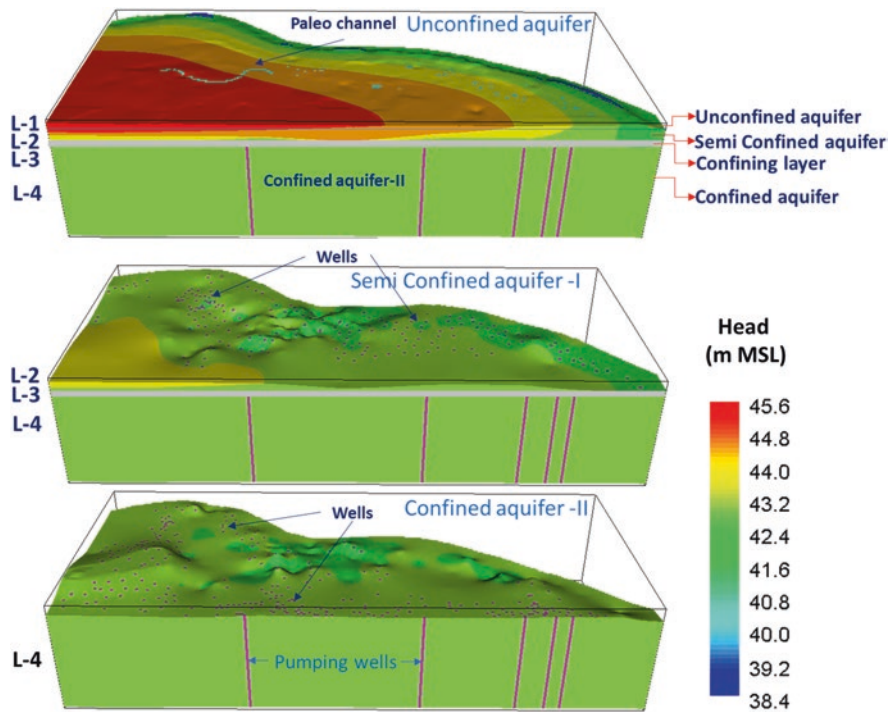


Fig. 9.14 Model Transient hydraulic initial heads of different aquifers

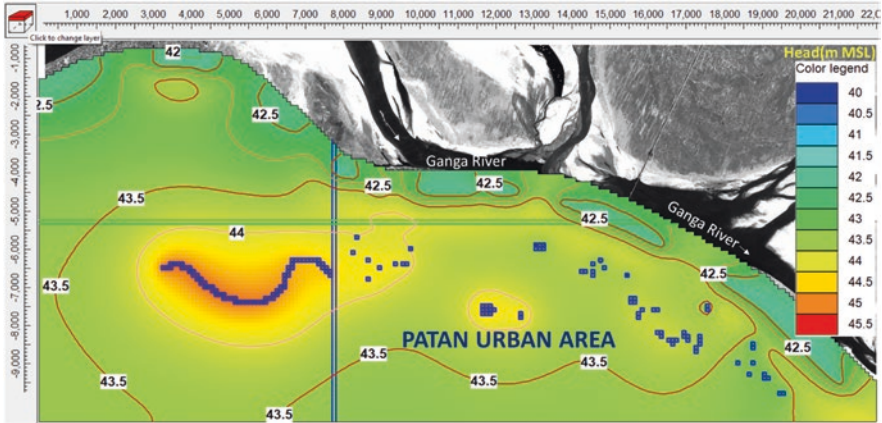


Fig. 9.15 Simulated head of the upper aquifer (layer-1) at the end of 10th year

have been treated as time-variant specified head boundaries in the development of the model (Figs. 9.12 and 9.13). The vast stretch of the Ganga river has been treated as a head-dependent flux boundary in the development of the model (Figs. 9.12 and 9.13). This model boundary varies with monthly river flow stages.

2.3 Model Simulation

Aquifer behavior has been simulated for 10 years (Figs. 9.15 and 9.16) with projected population growth and urban water need. The model has been simulated on a monthly stress period mainly to understand the impact of fluctuating river flow stages of the Ganga river. The model has been calibrated with the initial observed value, and it has been used for long-term prediction (Fig. 9.17). The 10 years of simulation has been found reasonable to understand the river and aquifer interactions as well as long-term aquifer behavior of the upper and lower aquifer (layer-1 and layer-4) under different external stresses. This has helped to predict the likely impact on the aquifer due to the heavy utilization of the lower aquifer to meet the drinking and domestic water demand of the entire Patna urban population.

3 Results and Discussion

The simulated results of the 10-year period with a stress period length of 1 month have indicated that the water table in some parts of the upper aquifer (unconfined) has a rising trend (Fig. 9.19). This may be due to negligible utilization of groundwater from this aquifer, and water logging has increased with time due to drainage

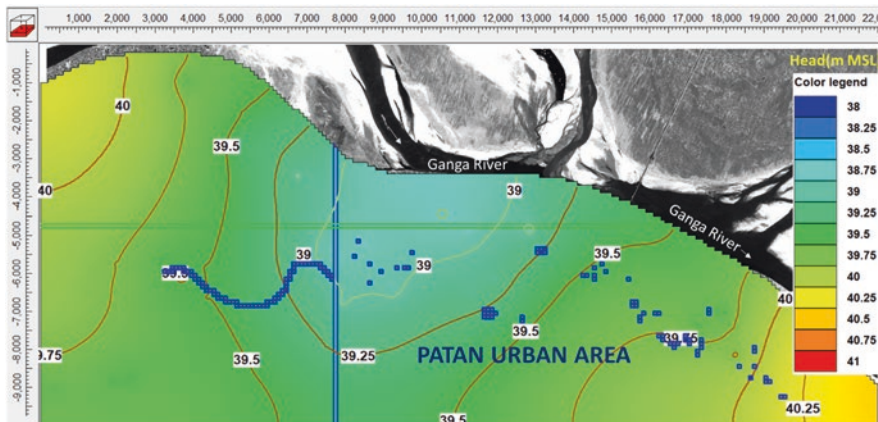


Fig. 9.16 Simulated head of the deep aquifer (layer-4) at the end of 10th year

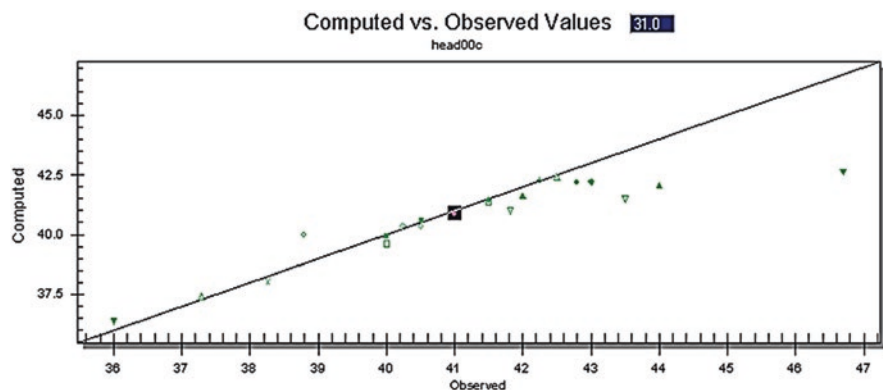


Fig. 9.17 Observed and computed head plot showing model calibration

congestion. Leaking soak pits and underground drainage systems are another source of recharge to the upper aquifer. The model simulation has indicated a 4.5–5.5 m decline in the hydraulic head during 10 years in the central area close to the river bank (Fig. 9.18). This area is part of the densely populated old part of town and a greater number of closely spaced high discharge tube wells operate in the area to meet the water demand of the urban population. It has also been observed that there will be an overall drop of more than 3 m in the hydraulic head within the entire PUA. It is likely to be a 0.3 m/year drop in the hydraulic head. The interfering cone of depressions of individual large volume pumping wells is now in the lower (confined) aquifer which has created a large cone of depression in the central part of the urban area. The hydraulic head of the lower (confined) aquifer near Patna maintains the level of river Ganga river in the north and Purpun river in the east and south, and observed seasonal fluctuation in the hydraulic head is due to direct or indirect interconnection between river and aquifer.

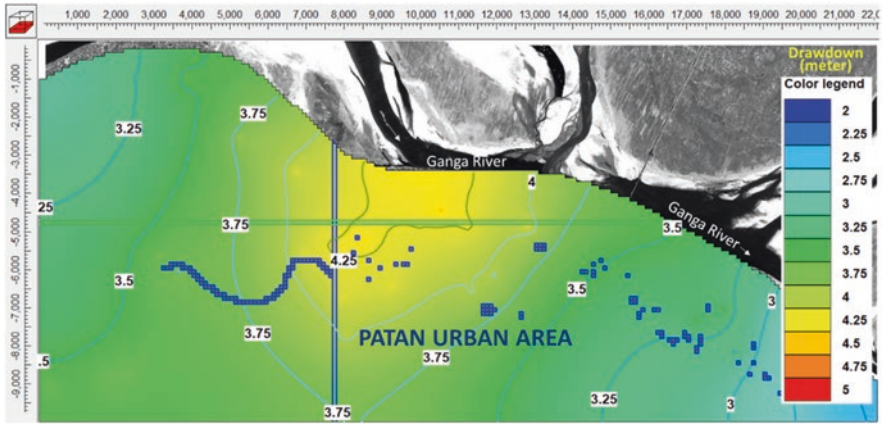


Fig. 9.18 Simulated drawdown of the deep aquifer (layer-4) at the end of 10th year

The model simulation has also indicated that the aquifer system of PUA is actively connected with the Ganga river and the river stages control the hydraulic head with time (Figs. 9.19 and 9.20). Its effects are more visible in the upper aquifer (Fig. 9.19). During the peak summer, the hydraulic head is about 43 m MSL near the river, whereas the river stage during this period remains at a level of 42 m MSL. During this period, aquifer outflow comes to the river. But during the peak flood period, i.e., the river at the highest flow stage (47 m MSL) situation reverses, river flow contributes to the near bank parts of the aquifers, and a rise in the hydraulic head has been overserved during this period. As the river flow stage decreases, the hydraulic head also starts declining. The effect of the river stage on the hydraulic head of the upper aquifer is visible up to 200–500 m inward from the river bank. The impact on the hydraulic head due to time-varying river stages is not visible in the lower (confined) aquifer (Fig. 9.20). But it cannot be concluded that there is no impact of river stage on the lower (confined) aquifer mainly because depletion in hydraulic head heavy pumping dominates and the aquifer has a continuous declining trend. Also, inflow from river to lower (confined) aquifer is relatively less than the rate of continuous constant outflow from aquifer, i.e., abstraction. This understanding is based on the flow water budget of the model (Fig. 9.21).

The river leakage to the aquifer system is about 116,000 m³/day at the end of the stress period 10, i.e., the end of September, which is also when the Ganga river flows at the highest stage. Once the river flow stage starts to decline, leakage from the river into the aquifer also starts to decline. At the end of December, situation gets reversed; aquifer system started contributing to the river. It has been found that outflow from the aquifer to the river will be 71,000 m³/day at the end of the stress period 13, i.e., the end of December, whereas river inflow to the aquifer will be negligible. The maximum inflow into the groundwater system surpasses the rainfall recharge to the aquifer system. Therefore, any long-term change in the river system in terms of flow volume and morphology will likely impact heavily on the groundwater system of PUA.

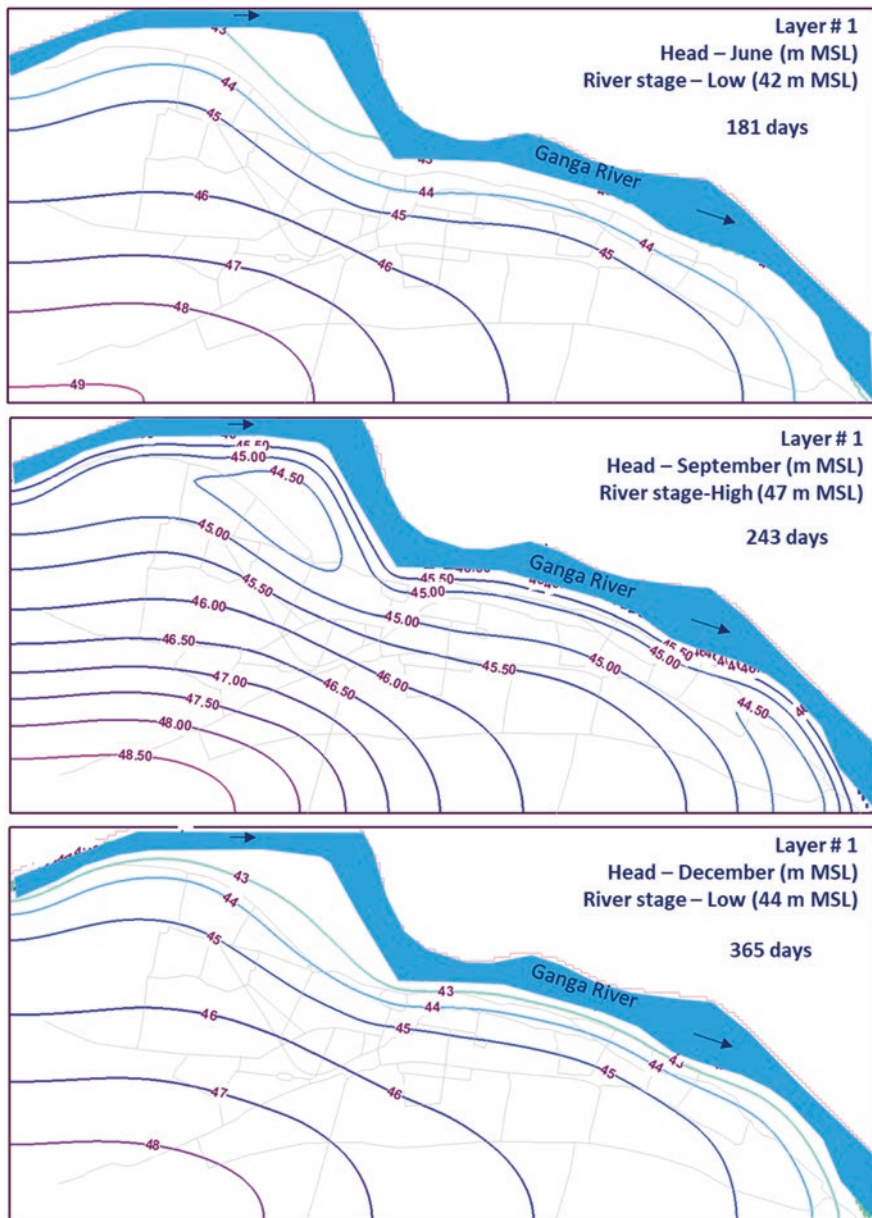


Fig. 9.19 Simulated hydraulic head of upper (unconfined) aquifer at different river stages

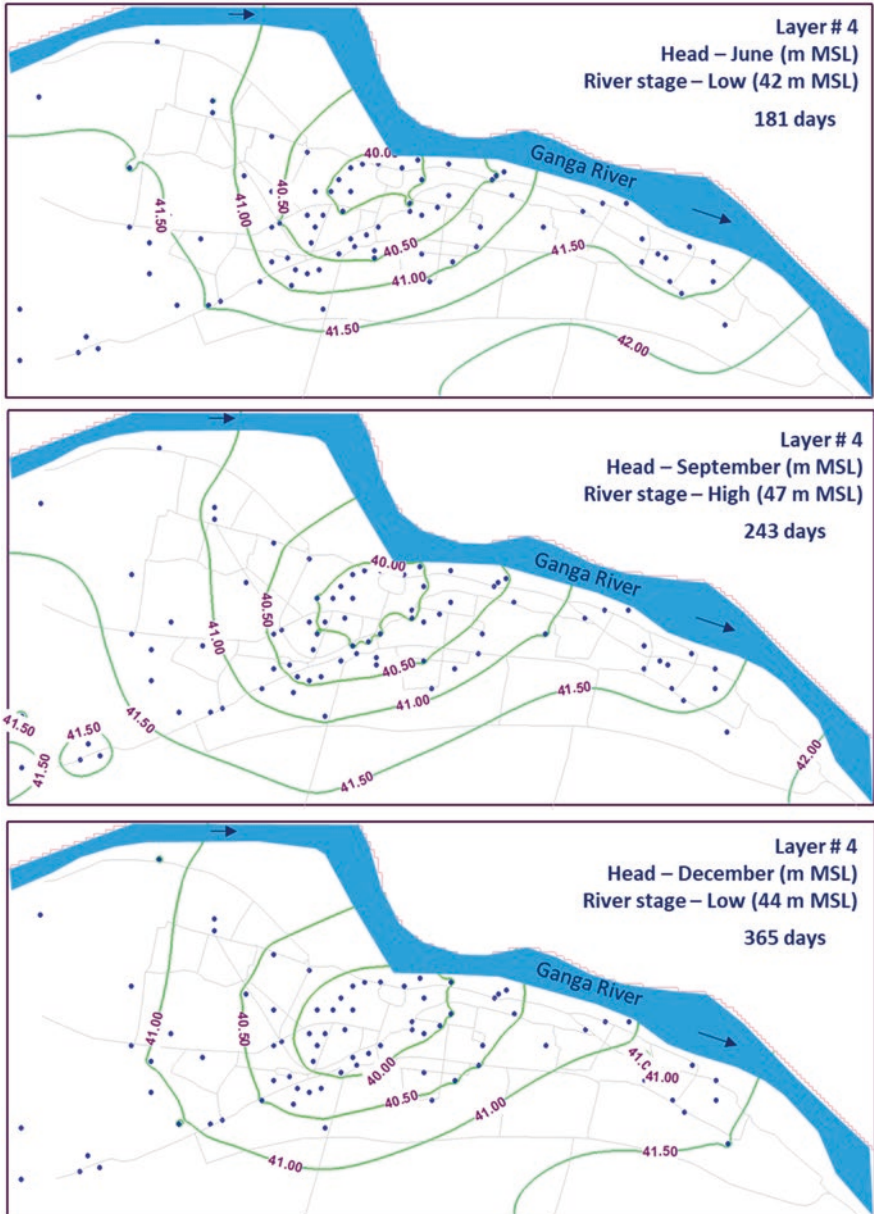


Fig. 9.20 Simulated hydraulic head of lower (confined) aquifer at different river stages

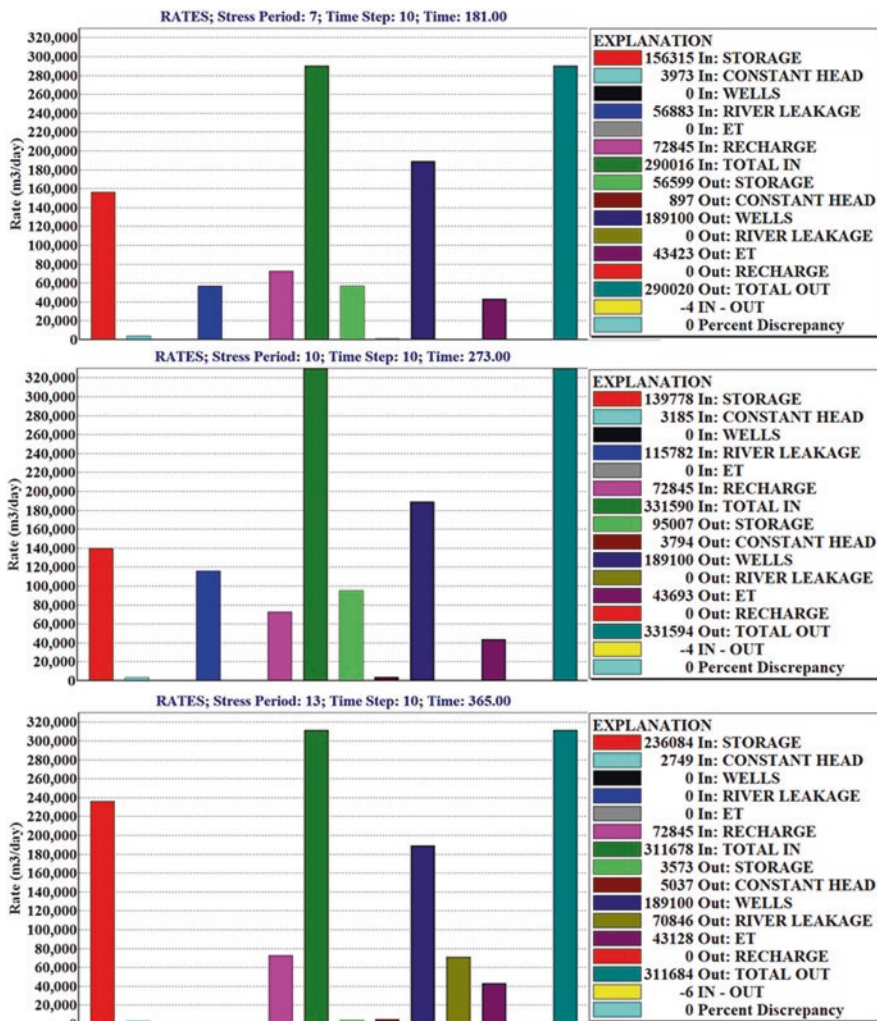


Fig. 9.21 Flow budget components during different stress periods (SP) of the year

4 Conclusions

The conceptual model has helped to understand the temporal and spatial behavior of the unconfined and confined aquifers under natural and human-induced stress conditions. It has been observed that there is a continuous decline in hydraulic heads in the lower (confined) aquifer. The hydraulic head of the lower (confined) aquifer is likely to decline at the rate of 0.3 m/year. This indicates that large volume abstraction from the lower aquifer for the town water supply is not sustainable. Results also indicated that high-rate pumping by individual tube wells interferes with each other, and in the long run, a large composite cone of depression will be created within the central part of the urban area. The new well fields must be shifted outside the

composite cone of depression to avoid further deepening and should be uniformly distributed over large areas. The overused confined aquifer cannot be replenished through artificial recharge due to the high hydraulic head of both the upper and lower aquifer. At the same time, the artificial recharge system likely creates a risk of aquifer contamination as recharged water will directly reach into the capture zone of operating tube wells. Engineering measures need to be adopted to keep the water level of the upper aquifer below the ground level; otherwise, there will be risk of entering urban pollutants into the aquifer. The study has indicated a strong interaction between the Ganga river and the aquifer system inflow, and outflow from the aquifer is significant compared to the other components of inflow into the aquifer. It has been observed that the river morphology of the Ganga river has dynamic flow and drastic changes in the river course near Patna town, which is connected to the groundwater system. The vast low-lying flood plain is the main source of recharge to the aquifers, and it guides the seasonal fluctuation in the aquifer. Therefore, protection of flood plain from urbanization is one of the important aspects of avoiding long-term abrupt changes in aquifer behavior.

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