
Hydrogeological environment and groundwater occurrences of the alluvial aquifers in parts of the Central Ganga Plain, Uttar Pradesh, India

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Abstract A detailed hydrogeological investigation was carried out in parts of the Central Ganga Plain, India, with the objective of assessing the aquifer framework and its resource potential. The area was studied because of its dual hydrogeological situation, that is water logging and soil salinization in the canal command areas and depletion of aquifers in the western part of the basin. A comprehensive investigation of the aquifer system between the Ganga River and Kali River revealed its lateral and vertical dimensions and hydrogeological characteristics. Moreover, study of the groundwater occurrences, movements and behaviour, in terms of water level fluctuation with time and space, confirms the coexistence of over exploitation as well as water logging in the area.

Résumé L'objectif de cette étude hydrogéologique détaillée de portions de la Plaine Centrale du Gange est de déterminer la structure aquifère et la ressource potentielle. L'intérêt de la zone repose sur sa dualité du point de vue hydrogéologique, les zones influencées par le canal présentent une remontée de la nappe avec une salinisation des sols, la portion Ouest du bassin présente une baisse du niveau des aquifères. Par cette étude, le système aquifère compris entre la rivière du Gange et la rivière Kali révèle ses dimensions latérales et verticales ainsi que ses caractéristiques hydrogéologiques. De plus, l'étude des événements, des mouvements et du régime hydrogéologique affectant le niveau phréatique confirme la co-existence de surexploitation et de saturation des sols dans la région.

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Resumen Una investigación hidrogeológica detallada se llevó a cabo en partes de la Llanura de Ganga Central, India, con el objetivo de evaluar la estructura del acuífero y su potencial del recurso. El área fue estudiada por su doble situación hidrogeológica, es decir la saturación con agua y salinización de suelos en las áreas dominadas por el canal y vaciamiento de acuíferos en la parte occidental de la cuenca. Una investigación completa del sistema acuífero entre el Río Ganga y el Río Kali, reveló sus dimensiones verticales y laterales y las características hidrogeológicas. Además, los estudios sobre la ocurrencia del agua subterránea, sus movimientos y comportamiento, en lo que se refiere al nivel de agua, y a su fluctuación en el tiempo y el espacio, confirma la co-existencia en el área de sobre-explotación así como de saturación con agua.

Keywords India · Central Ganga Plain · Aquifer system · Hydraulic properties · Groundwater flow

Introduction

The study area is a part of the subtropical Central Ganga Plain covering an area of about 1,340 km² in the Aligarh and Etah districts of Uttar Pradesh, India. The Ganga Basin is one of the most densely populated regions and one of the largest groundwater reservoirs in the world. The average population density is 550 individuals per km² and about 42% of India's population occupies the basin. For several decades alarming population growth, fast urbanization and rapid industrialization in this plain have caused various geo-environmental hazards (Ansari et al. 2000). Agriculture is the main stay of life, which depends heavily on water.

The study area lies between the latitude 27°47' and 28°09'N and longitude 78°12' and 78°45'E (Fig. 1). The area receives 70–80% of its annual rainfall of 754 mm from the Southwest monsoon during the month of July and August.

Physiographically, the area is divided into (i) low valley of the Ganga River (ii) Eastern Upland (iii) Nim River–Kali River interfluves. The Ganga and Kali rivers form the northeast and southwest limit of the area. The lower Ganga canal is fed by the Ganga River in the upstream side.

Out of the total water resources of the Ganga–Kali sub-basin, 20% is derived from the surface water and 80% from the groundwater sources. The Anupshahar branch of the

Fig. 1 Location map of the study area

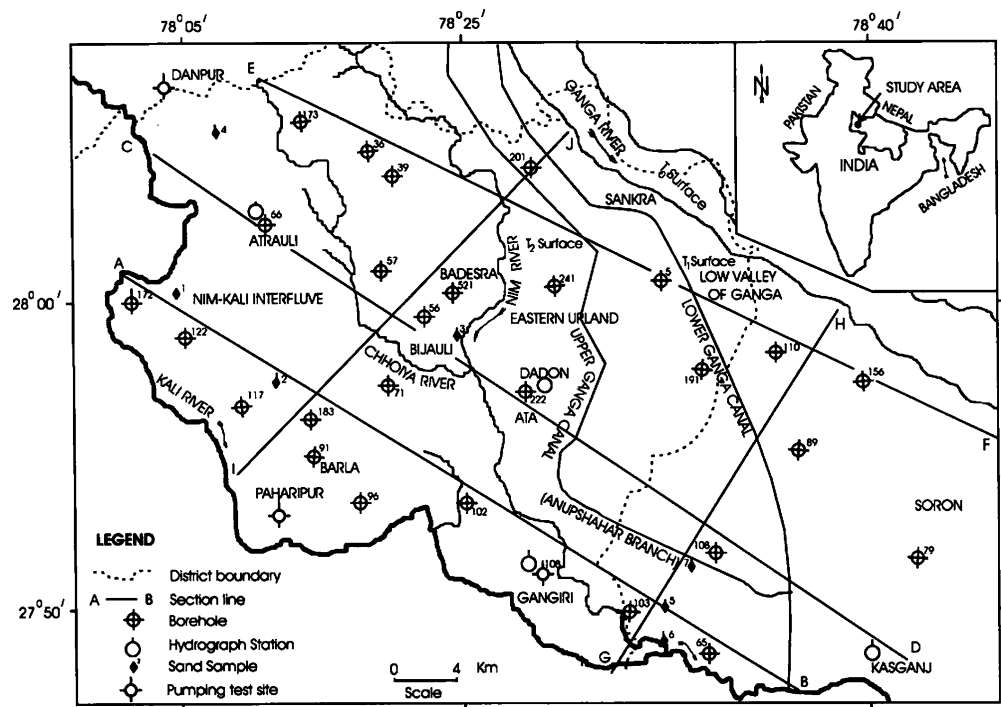
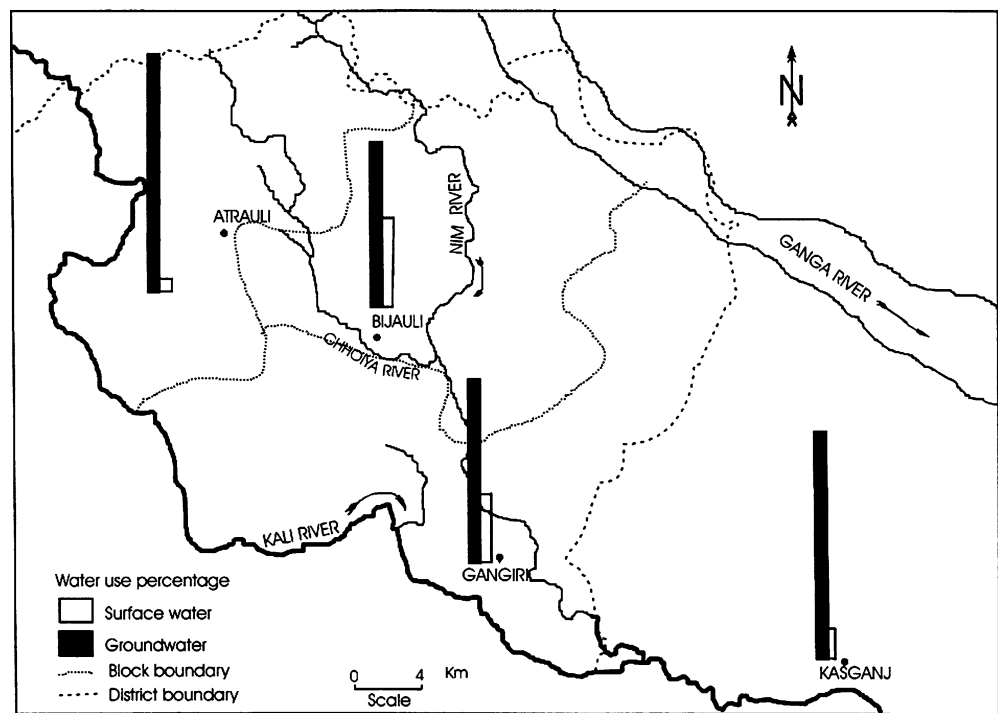


Fig. 2 Comparison of water use in the study area



upper Ganga canal supplies the surface water for irrigation mainly to Nim–Ganga interfluve known as the Eastern Upland and also the area lying west and southeast of Kasganj town. Administratively, the study area is divided into various integrated development blocks. The integrated blocks are small administrative units of a district, in order to carry out the developmental plan at the micro level. The block-wise water usage patterns are given in (Fig. 2). The Kali–

Ganga sub-basin presents a dual situation whereby there is depletion of the aquifer in the western part of the basin and water logging in the Eastern Upland, resulting in soil salinization in canal command areas, a feature common to many irrigation commands of surface water projects in India. The irrigation command areas are recharged not only by rainfall infiltration but also by seepage from reservoirs, canals, distributaries and field channels and percolation of applied

irrigation water. Water logging is said to occur when the water table rises to within the root zone of crops. Direct evaporation of groundwater from the capillary fringe and advanced stages of groundwater as well leads to the salinization of soil (Karanth 1987).

The aim of this report is to present an integrated study on the geological and hydrogeological aspects, for the better understanding of the aquifer system.

Geomorphology

Climatic and tectonic changes with time have caused the development of various geomorphic surfaces and features, which are regionally persistent in the plain (Singh 1996, 2004). Three regional geomorphic surfaces are broadly identified in the study area of the Aligarh-Etah region, which are designated as T_0 , T_1 and T_2 surfaces (Umar 1990). The T_0 -surface is made up of the active channel of the Ganga River and its flood plain. During the annual high water stage of the monsoon time, this surface floods. T_1 surface is located 5–10 m above the T_0 surface, which shows many meander scars and a prominent meander scroll. T_2 surface is upland surface and shows presence of many abandoned drainage and meander channel belts. T_0 , T_1 and T_2 are shown in Fig. 1.

Geologic setting

The Ganga Plain is an active foreland basin formed as a result of the continental collision between the Indian Plate and the Asian Plate. A fairly detailed account of the subsurface geology and basement tectonics of the Ganga Plain is given by Sastri et al. (1971) and Rao (1973) and the geological evolution of this plain and its depositional model is given by Singh (1996, 2004).

Exploratory drilling by the Oil and Natural Gas Commission (ONGC) and the Central Groundwater Board (CGWB) in search of petroleum and groundwater respectively has generated drilling data down to the basement of the basin and helped to establish the stratigraphic sequence. Two deep exploration wells drilled at Kasganj and Ujhani (see Fig. 3) are located on either side of the Ganga River. The bedrock encountered in Kasganj at a depth of 620 m is lower Bhandar limestone. The same limestone was encountered at a depth of 967 m at Ujhani about 10 km further north across the Ganga River indicating the possibility of fault along which the present Ganga River flows (Umar 1990). Based on a geological cross section prepared using five lithologies (Fig. 3) the summarized stratigraphic sequence is given in Table 1.

The area is underlain by Bundelkhand granites which form the basement complex that is unconformably overlain by the Upper Vindhyan sequence, the Siwaliks and finally by the Quaternary alluvium. The Quaternary alluvium contains alternate beds of sand and clay down to 360 m below ground level (mbgl) that contain several aquifer systems in the Central Ganga Basin. Various grades of sand form the

granular zones varying from fine through medium to coarse micaceous sands (see Table 2).

Hydrogeology

A systematic hydrogeological investigation was carried out in the area. A network of 160 observation wells was established. The wells were located in such a way that one well represented a 4 km² area. Repeat measurements of water level were carried out in the months of June and November 1988 and 1989. Lithological logs of boreholes were collected to prepare various cross sections. In addition to this, aquifer parameters were determined using standard techniques.

Aquifer evolution

The Ganga River and its tributaries have given rise to various aquifer types through its varying flow regime over thousands of years. The evolution of aquifers in the fluvial system is dependent upon the hydrodynamics of the flow regime geology and topography of the terrain leading to a fluvial clastic deposition system, which is typically represented by a channel, flood plain and back swamps deposits (Umar 1990; Ala Eldin et al. 2000). The typical channel deposits of the Ganga River from the bottom upwards comprises of coarse sand mixed with gravel, medium to fine sand, silt and a capping of thin clay. This clay cap and some fine sand layers are washed away during the succeeding flood period and a fresh body of sand is deposited again each year during the flood thus building up a thick terrigenous clastic deposit until the river changes its course as a result of some tectonic control. These thick bodies of sand provide the best potential for viable aquifers.

The flood water erodes the river bank, transports the materials and finally deposits the fine to medium sand particles over the flood plain area during the monsoon period. The lenticular bodies of sand form moderate aquifers in comparison to the highly permeable aquifer of channel deposits. The flood water moves further down the slope to the low lying areas where the suspended material settle to form a lensoid body of sand followed by the finer clastic material i.e. clay. Thus, it forms enclaves of sand bodies intercalated within thick clay sequences. Such bodies of sand have low potential as aquifers. These sequences are typically

Table 1 Sequence of geological formation in parts of Central Ganga Plain

Sequence of geologic formation	Depth range (mbgl)	Age
Alluvium	0–360	Quaternary
Siwaliks (Upper & Middle)	360–620	Neogene
Lower Bhandar Limestone (Upper Vindhyan)	620–2061	Upper Proterozoic
Bundelkhand Granite (basement complex)	>2061	Archean

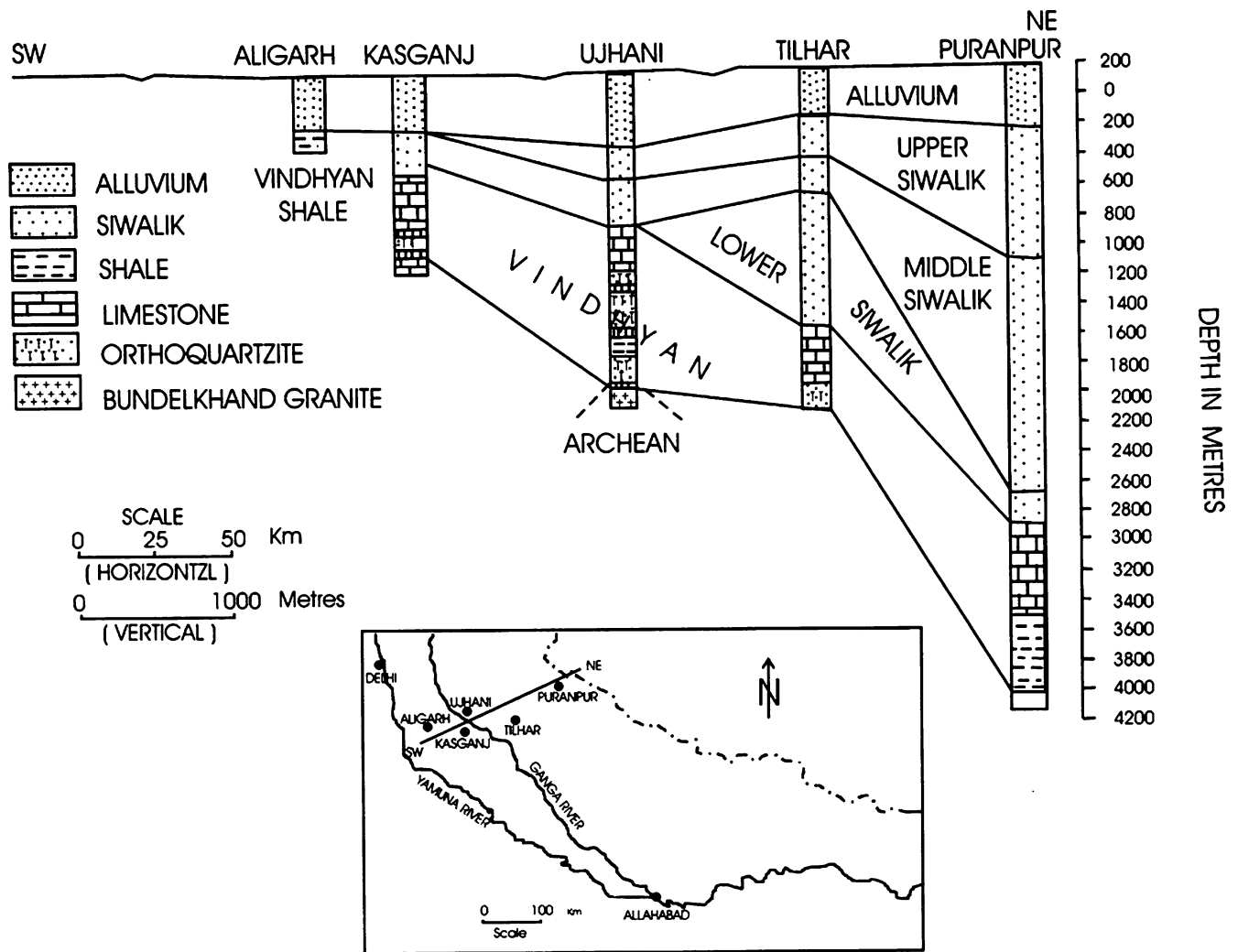


Fig. 3 Geological cross-section and borehole logs (modified after Sastri et al. 1971)

Table 2 Grain size analysis from sample sites located in Fig. 1

Sand sample no	Location	Effective grain size d_{10} (mm)	Uniformity coefficient	Hydraulic conductivity (m/day)	Typical sand type
1	Chaumuhan	0.15	1.7	129	Coarse sand
2	Ghazipur	0.18	4.4	169	Coarse sand
3	Runpan	0.07	1.9	26	Fine sand
4	Kheria	0.07	1.9	25	Fine sand
5	Dholna	0.13	1.6	87	Medium sand
6	Firozpur	0.12	1.7	74	Medium sand
7	Ghinauna	0.13	1.6	98	Med-coarse sand

representative of back swamp environments. Subsequently the river changes its course as a result of some tectonic movement. Thus the position of the channel, flood plain and back swamp deposit continuously change with the passage of time. That is why no continuous body of sand or clay except under certain extraordinary conditions is encountered in a single drill hole. The above lithological variations result from the mode of deposition, which is governed by the constantly migrating nature of the Ganga River.

Aquifer system

The hydrogeological cross-sections A–B, C–D, E–F, G–H and I–J (shown in Figs. 1 and 4) are distributed across the entire area, in which three cross-sections run from northwest to southeast and two sections (G–H and I–J) from southwest to northeast. These sections show a 2–3 layered aquifer system up to 100 m in depth. In section A–B (Fig. 4a) the clay bed starts attaining thickness from

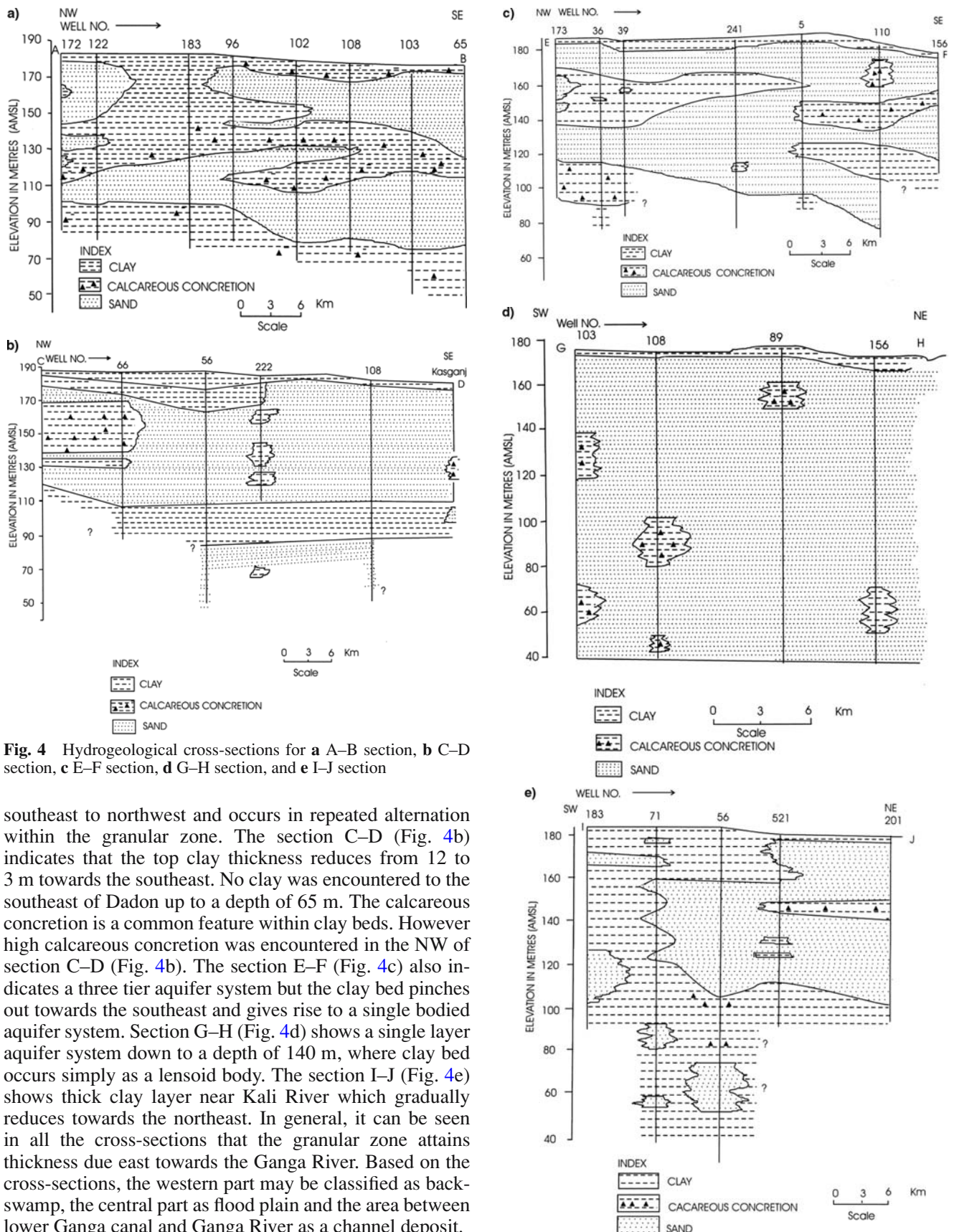


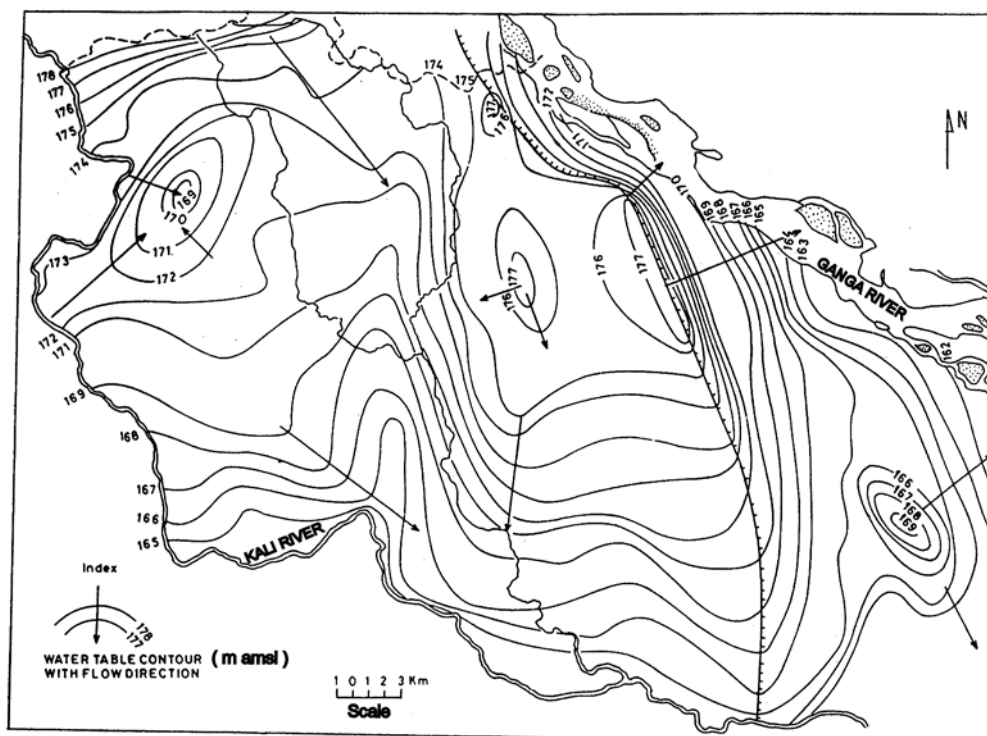
Fig. 4 Hydrogeological cross-sections for **a** A–B section, **b** C–D section, **c** E–F section, **d** G–H section, and **e** I–J section

southeast to northwest and occurs in repeated alternation within the granular zone. The section C–D (Fig. 4b) indicates that the top clay thickness reduces from 12 to 3 m towards the southeast. No clay was encountered to the southeast of Dadon up to a depth of 65 m. The calcareous concretion is a common feature within clay beds. However high calcareous concretion was encountered in the NW of section C–D (Fig. 4b). The section E–F (Fig. 4c) also indicates a three tier aquifer system but the clay bed pinches out towards the southeast and gives rise to a single bodied aquifer system. Section G–H (Fig. 4d) shows a single layer aquifer system down to a depth of 140 m, where clay bed occurs simply as a lensoid body. The section I–J (Fig. 4e) shows thick clay layer near Kali River which gradually reduces towards the northeast. In general, it can be seen in all the cross-sections that the granular zone attains thickness due east towards the Ganga River. Based on the cross-sections, the western part may be classified as back-swamp, the central part as flood plain and the area between lower Ganga canal and Ganga River as a channel deposit.

In the present study, aquifers down to the depth of 140 m below ground level were studied, however the lithology of

Fig. 4 Continued

Fig. 5 Water table contour map (June 1988)



the exploratory well drilled at Kasganj shows that alluvium is 360 m thick which possibly contains two to three aquifers separated by clay layers. The site in reference is located close to the Ganga River, hence the granular zones predominate the clay layers.

The near surface groundwater body occurs under water table conditions, while deeper aquifers occur under confined conditions. The depth of water varies between 2 and 16 mbgl. The deep water level is generally observed in the western part of the study area, which ranges between 8 and 16 mbgl whereas shallow water levels leading to swampy conditions are observed in the low valley of Ganga and along the lower and upper Ganga canals. The water table fluctuation revealed a trend of varying degree throughout the basin, which ranges between 0.5 and 2.0 m.

The elevation of the water table ranges between 179 m above sea level (msl) in the northwest to 162 m amsl in the southeast. The regional groundwater flow is in a NW-SE direction, which follows the general topography of the area (Fig. 5). The hydraulic gradient is steeper in the east and south close to the Ganga and Kali rivers than the central part of the basin, indicating that the sediments are finer and have low permeability.

Aquifer parameters

Grain size analysis

Pumping test data for the evaluation of aquifer parameters are not available for the entire basin, hence seven sand samples were collected for grain size analysis (Fig. 1 and Table 2). The parameters effective grain size and hydraulic conductivity were evaluated. The hydraulic conduc-

tivity has been determined using the formula of Uma et al. (1989).

$$K = Ad_{10}^2$$

where K is the hydraulic conductivity in cm s^{-1} . The unit of K is converted to m/day and given in Table 2. A is a constant and d_{10} is the effective grain size.

The value of A was established as 6 for sandy aquifers. Effective grain size (d_{10}) is the most important parameter among those governing the permeability of a granular medium. The grain size of the aquifer material ranges between 0.07 and 0.181 mm indicating that the sand size ranges from fine to medium. The results of uniformity coefficient reveal that in general, the samples show a value of uniformity coefficient less than 2, hence their porosity is high. The hydraulic conductivity ranges between 25 and 170 m/day, which is at the higher side. At places the variation in the hydraulic conductivity is more than 50% therefore, these values were not utilized in isopermeability mapping.

Pumping test data analysis

The pumping test data of two sites at Danpur and Paharipur were analysed during the present study using the methods of Theis (1935) and Jacob and Cooper (1946). The results are given in Table 3.

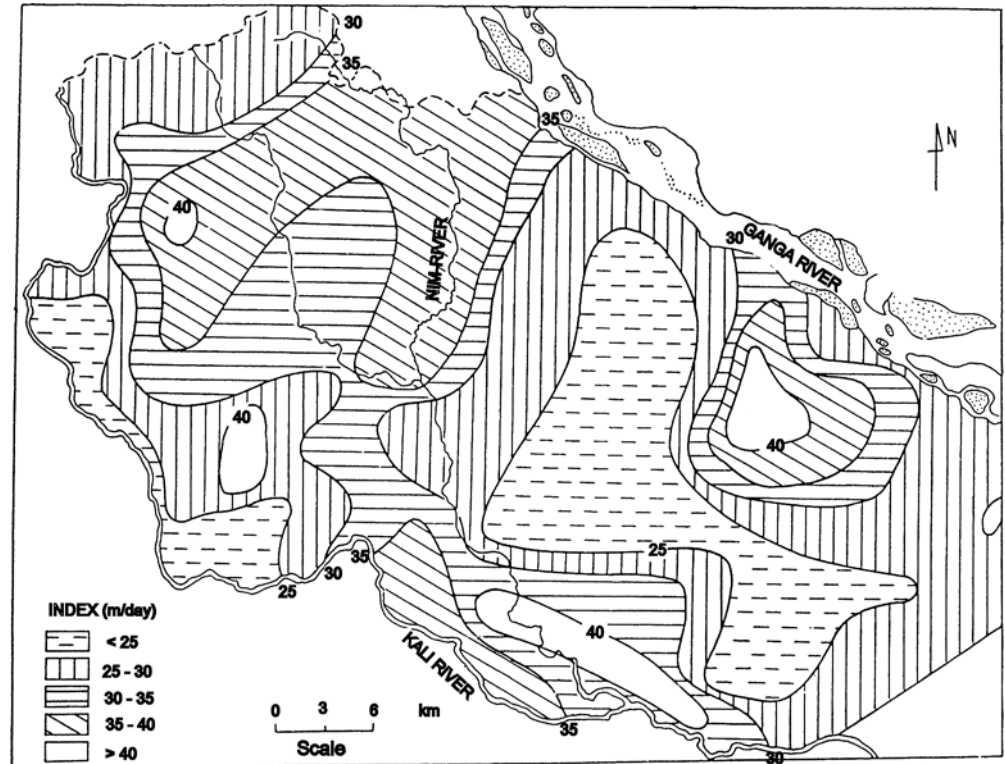
Isopermeability map

The Logan's (1964) approximation was used to determine the permeability which states,

$$T = 1.22 Q/S_{mw}$$

Table 3 Pumping test data analysis

Location	Transmissivity (m ² /day)	Hydraulic conductivity (m/day)	Specific yield (%)	Storativity
Paharipur	2060	73	8.9	–
Danpur	528	38	–	7.75×10^{-4}

Fig. 6 Isopermeability map of the area (Permeability in m/day)

where T is the transmissivity (m²/day), Q the discharge (m³/day), and S_{mw} is the maximum drawdown in pumped well (m).

Using the discharge and drawdown data of existing boreholes, an isopermeability map was prepared using an interpolation technique (Fig. 6). Five isopermeability zones were demarcated i.e. (i) <25 m/day (ii) 25–30 m/day (iii) 30–35 m/day (iv) 35–40 m/day (v) >40 m/day. The permeability range is 25–30 m/day in the area close to Kali River but gradually increases due east towards the Nim River with some local variations. Although the area is an alluvial track, there is a remarkable variation in the permeability. This may possibly be attributed to the subtle variation in the grain size, sorting characteristics and grain packing, representing microscopic inhomogeneities that control permeability and thus the fluid flow characteristics.

Discussion

The two extreme hydrogeological situations are present in the study area and they are in hydrogeological equilibrium based on the last 25 years data. This can be explained from the water table contour map and hydrographs. A perusal of the water table contour map shows that the major slope of

the water table is towards the southeast following the general topography of the area. In the eastern part, the slope of the water table is towards the east, parallel to the general slope of the ground as the aquifer is unconfined. The hydraulic gradient is steeper in the east close to Ganga and Kali rivers than the central part of the basin, indicating sediments are finer and have low permeability. Further, the contour behaviour shows both the Ganga and Kali rivers are effluent in nature except close to Atrauli where a groundwater trough has developed due to heavy withdrawal of groundwater through shallow and deep tube wells. Here the groundwater flows from west to east, which imparts an influent character to the Kali River, which is otherwise basically effluent in nature. The reversal of hydraulic gradient is the result of the excessive withdrawal of groundwater in the area arriving at a new steady state. It is further verified through the analysis of the two hydrographs (Fig. 7a and b) falling in the western part of the basin, which show that the water table in this unit has a declining trend where the average rate of decline is estimated to 0.34 m/year (Umar et al. 1999).

The situation is reversed in the Nim–Ganga interfluvium. Here the area is criss-crossed by a canal network and because of seepage from unlined canals, three groundwater mounds have formed along the lower and the upper Ganga canal. These mounds are sharing water from their eastern

flanks with the Ganga River and from the western flank with the Nim River. The aquifer system in this part is very much receptive of the massive seepage leading to the formation of these mounds. The representative hydrograph (Fig. 7c) from this part does not show any significant change in their behavior, which confirms the surface water contribution.

The dual situations in the area are resultant of heavy withdrawal of groundwater through a large number of tubewells both shallow and deep. The demand for groundwater for irrigation and municipal purposes has lead to the declining trend of water level. When there is a heavy rain, aquifers are recharged but withdrawal goes on throughout the year while the rainfall recharging the aquifer is limited to the monsoon months i.e. June to September. Hence, it is very difficult for the monsoon recharge to cope with the declining nature of the water table throughout the year, unless some aquifer recharge measures are undertaken. The water logging situation along the upper Ganga canal is a result of rampant seepage all along the canal bed into the aquifer

below it, resulting in a rapid rise in the water table leading to acute water logging all along both the banks of the upper Ganga canal. Further, the specific yield of the aquifer is very low and that combines with anthropogenic actions whereby on one side there is a heavy pumping and on the other continuous seepage, resulting in a sharp lowering of the water table in the first zone as well as a rise in the water level in the other zone. The situation is further affected by a low permeability zone in between the two zones (Fig. 6). The low permeability zone could be the result of the presence of fine sand to silt acting as a barrier and the dual hydrogeological situation is a permanent feature.

A comparison of the water level of June 1988 and June 2002 for selected wells from the Nim–Kali and Nim–Ganga interfluves was made. The water levels of these wells are given in Table 4. A perusal of the table shows that a similar trend is still continuing in the basin.

A water balance study of the entire area was attempted. The water balance result shows a surplus of 169 million m³

Fig. 7 a Hydrograph at Atrauli (1975–1998), b Hydrograph at Gangiri (1977–2003), c Hydrograph at Kasganj (1975–1999)

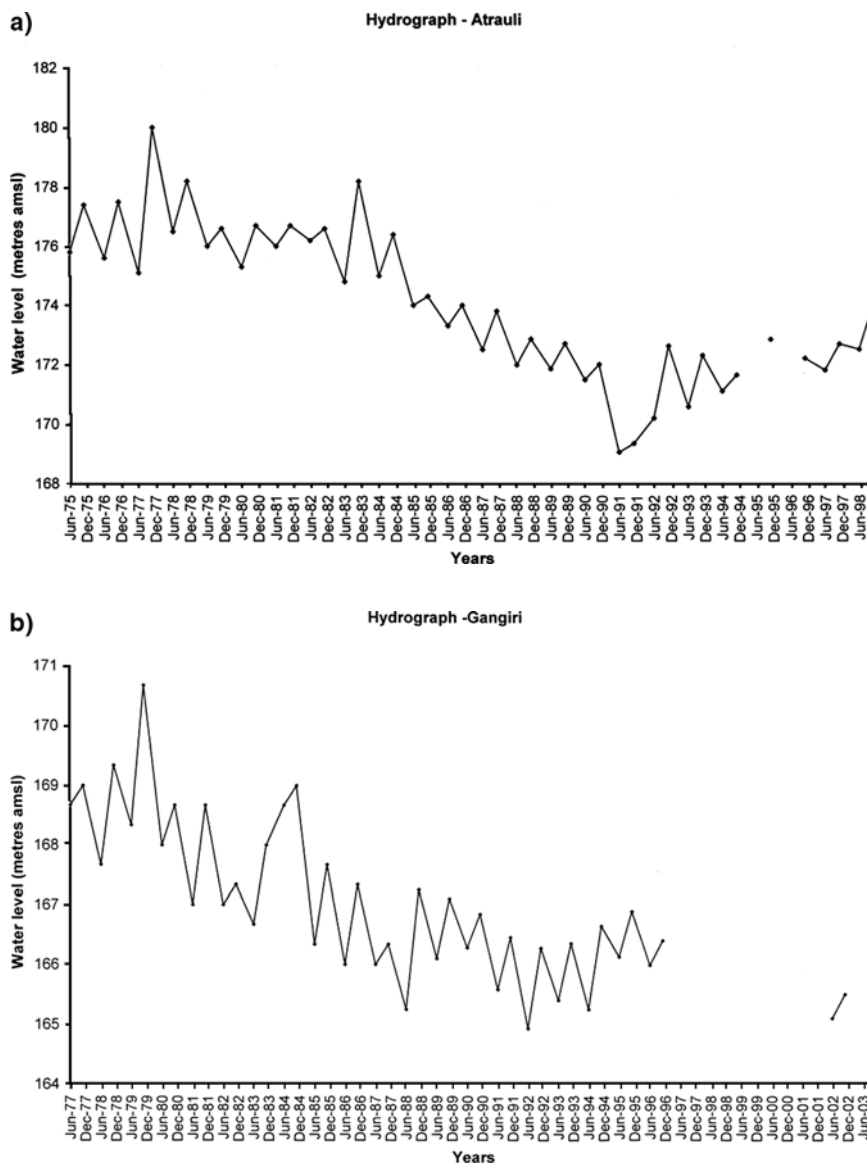
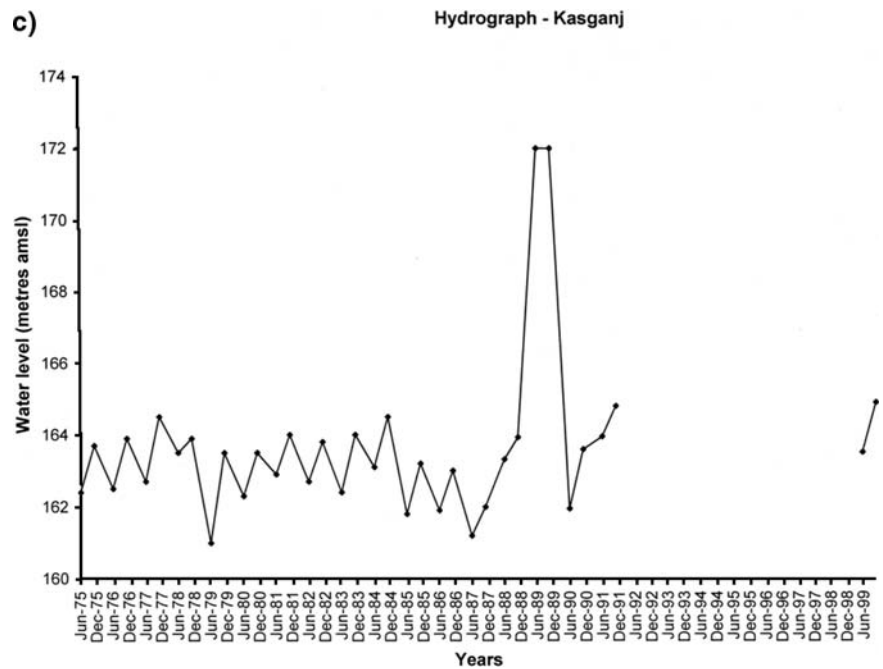


Fig. 7 Continued

**Table 4** Comparison of water level of June 1988 and 2002

Well location	Depth to water table (mbgl)		Rise (+)/decline (-)
	1988	2002	
Nim-Kali interfluv			
Atrauli	14.68	—	—
		11.66 ^a	—
Bijauli	12.55	14.06	—
Badesra	10.60	12.2	—
Nim-Ganga interfluv			
Kasganj	9.25	8.49	+
Soron	8.4	5.83	+
Ata	5.70	5.02	+

^aPiezometric surface, because the well was dry

(Umar 1990), although there is a surplus of groundwater but still the eastern part of the area is showing over exploitation which indicates that this part is not getting contribution from Nim-Ganga interfluv because of certain inherent hydrogeological characteristics. In the latest reconnaissance survey (year 2002) it was found that the groundwater situation is almost the same and the similar trend of utilization is continued which is also evident from Table 4, thus it is believed that the situation may not have changed the component of the groundwater balance drastically. However, if the recommendations presented below are implemented, the groundwater situation in each area is expected to change and then a revised groundwater balance should be made.

Conclusion

The Ganga River and many tributaries have given rise to various aquifer types of different dimensions, making

up complex flow regimes. The granular material consists of fine through medium to coarse micaceous sand mixed with gravel. The various hydrogeological cross-sections depict three-tier aquifer systems down to 140 mbgl. These aquifers finally merge with each other and behave as a single body aquifer system due to the discontinuities of the clay layer. The near surface groundwater occurs under water table conditions while deeper aquifers occur under confined conditions. The water table varies between 179 and 162 m amsl and the regional slope of groundwater is from NW to SE and follows the general topography of the area. In most parts of the area, Ganga and Kali rivers behave as effluent streams. The hydrographs of Nim-Kali interfluves show a progressive decline of 0.34 m/year. The aquifer parameters such as transmissivity and specific yield at Paharipur pumping test site are 2060 m²/day and 8.9%, respectively. However, at Danapur pumping test site the transmissivity and storativity values are 528 m²/day and 7.75 × 10⁻⁴, respectively. The values of *K* (hydraulic conductivity), determined through grain size analysis (the aquifer being alluvial), provide reasonable estimates. The coexistence of two hydrogeologically opposite situations provides only short-term steady state.

In order to achieve systematic exploitation without disturbing the natural hydrodynamic system, the following remedial measures are suggested.

1. In view of the declining water level, which is consequent to excessive withdrawal from the shallow aquifer, it is suggested that further exploitation of groundwater from the shallow aquifer should be restricted. Stress of heavy exploitation may be put to the second and third aquifer so that it is more evenly distributed.
2. Suitable artificial recharge techniques such as rehabilitation of ponds and dug wells should be practiced for recharge purposes during monsoon periods.

Construction of recharge pits is necessary where such structures are not available.

3. Groundwater should be pumped in the area between the Nim River and the Ganga River. This will help to reduce the problem of acute water logging along the lower Ganga canal.
4. Conjunctive use of surface water and groundwater resources is the optimal method of obtaining maximum possible water development.

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