Implications of Kali–Hindon inter-stream aquifer water balance for groundwater management in western Uttar Pradesh

Rashid Umar[1], M Muqtada A Khan[1], Izrar Ahmed[1] and Shakeel Ahmed[2]

[1]*Department of Geology, Aligarh Muslim University, Aligarh 202 002, India*
[2]*IFCGR, National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India*

The Kali–Hindon inter-stream region extends over an area of 395 km^2 within the Ganga–Yamuna interfluve. It is a fertile tract for sugarcane cultivation. Groundwater is a primary resource for irrigation and industrial purposes. In recent years, over-exploitation has resulted in an adverse impact on the groundwater regime. In this study, an attempt has been made to calculate a water balance for the Kali–Hindon inter-stream region. Various inflows and outflows to and from the aquifer have been calculated. The recharge due to rainfall and other recharge parameters such as horizontal inflow, irrigation return flow and canal seepage were also evaluated. Groundwater withdrawals, evaporation from the water table, discharge from the aquifer to rivers and horizontal subsurface outflows were also estimated. The results show that total recharge into the system is 148.72 million cubic metres (Mcum), whereas the total discharge is 161.06 Mcum, leaving a deficit balance of −12.34 Mcum. Similarly, the groundwater balance was evaluated for the successive four years. The result shows that the groundwater balance is highly sensitive to variation in rainfall followed by draft through pumpage. The depths to water level are shallow in the canal-irrigated northern part of the basin and deeper in the southern part. The pre-monsoon and post-monsoon water levels range from 4.6 to 17.7 m below ground level (bgl) and from 3.5 to 16.5 m bgl respectively. It is concluded that the groundwater may be pumped in the canal-irrigated northern part, while withdrawals may be restricted to the southern portion of the basin, where intense abstraction has led to rapidly falling water table levels.

1. Introduction

The study area which is a part of the central Ganga Basin is comparatively well endowed with groundwater resources. The high stress on groundwater due to abstraction of large quantities of groundwater through pumping for irrigation and domestic uses, has threatened the sustainability of agriculture development. It has been concluded therefore that it is necessary to restrict the exploitation of groundwater to its availability (Marechal *et al* 2002). The basic objective of groundwater resource evaluation is to estimate the total quantity of groundwater resources available, and their future supply potential in order to predict possible conflicts between supply and demand and to provide a scientific database for rational water resources utilization (Earth Summit 1992).

Previous hydrogeological investigations in the area were mainly carried out by the Central Groundwater Board (CGWB) and Groundwater Department of the Uttar Pradesh (U.P.) government. Aquifer modeling studies have been carried out in Krishni–Hindon inter-stream region adjoining the study area (Gupta *et al* 1979, 1985). They have assessed the stream aquifer interaction as well as conjunctive use of surface water and groundwater in the region.

Keywords. Groundwater balance; irrigation return flow; aquifer management; Muzaffarnagar; Uttar Pradesh.

J. Earth Syst. Sci. **117**, No. 1, February 2008, pp. 69–78

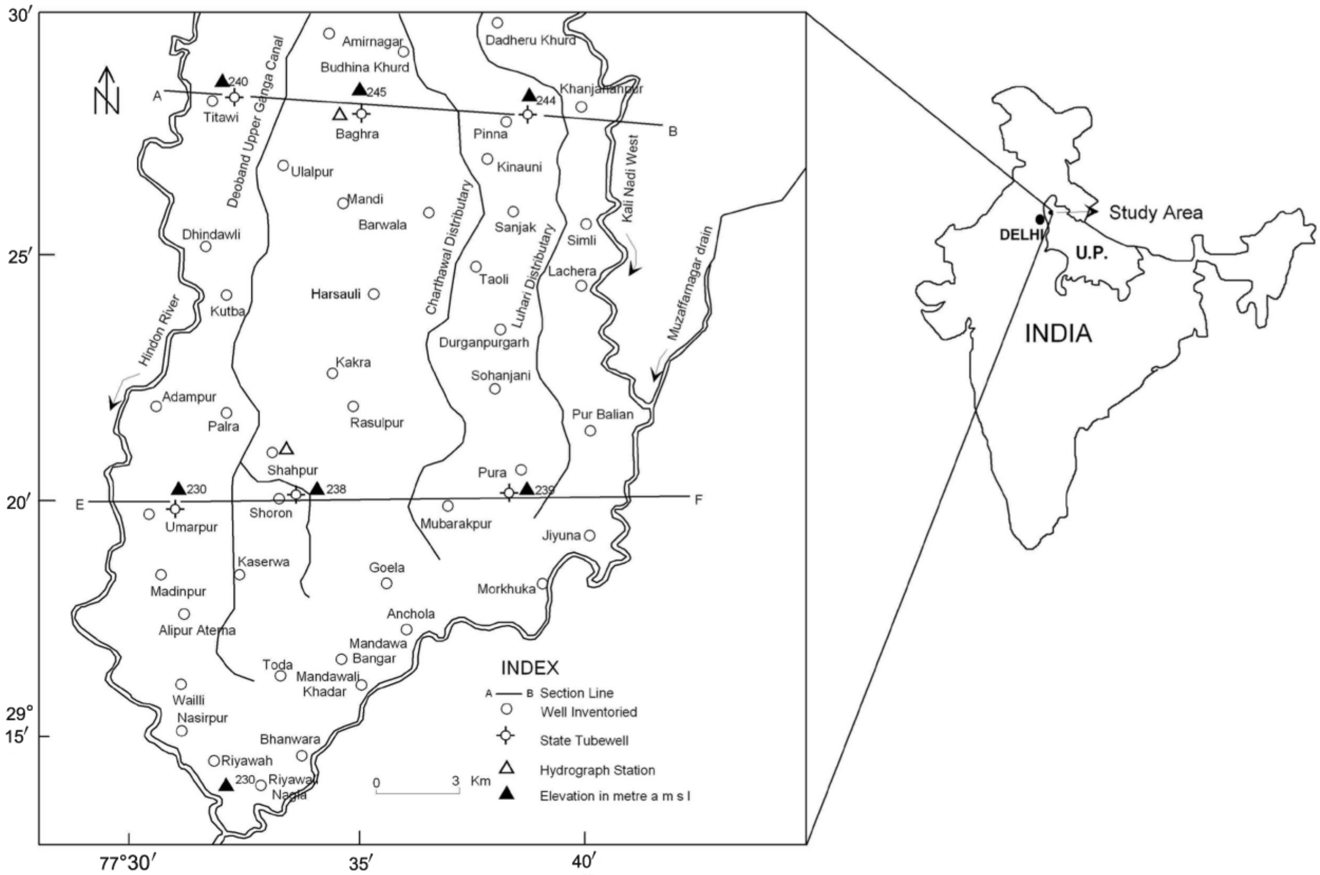

Figure 1. Base map of the study area.

Khan (1992) carried out systematic hydrogeological surveys in parts of Muzaffarnagar in field season during 1983–1984, and studied the first group of aquifers in detail. The two blocks Budhana and Shahpur were reported as over-exploited blocks. Kumar (1994) carried out reappraisal surveys in field season during 1992–1993 in parts of Muzaffarnagar and identified Baghra, Kairana, Uoon Budhana and Shahpur blocks as being over-exploited where the groundwater development has reached up to 142.15%. Further, he recommended that the exploitation of groundwater be stopped in these blocks.

As the Baghra and Shahpur blocks which cover the Kali–Hindon watershed are identified as critical blocks, the present study is significant because the water balance studies have been carried out afresh at microwatershed level.

Overexploitation and mismanagement create adverse impacts on groundwater regime. Quantitative evaluation of groundwater resources of an area or basin is an essential pre-requisite for its management. An attempt has been made in the present work to calculate the various components of the groundwater balance of the basin and enable conclusions relevant to groundwater management.

2. Area of study

The study area lies in the central part of the Muzaffarnagar district of the state of Uttar Pradesh, bounded on the east by the river Kali and on the west by the river Hindon. It lies between the latitudes 29°13′N and 29°30′N and longitudes 77°30′E and 77°45′E (figure 1) and covers an area of about 395 km^2. The whole area is fertile with sugarcane and wheat being the principal crops. The drainage of the study area is mainly controlled by the two perennial rivers which flow from north to south. In general, both the rivers are mature and meandering.

The area enjoys a sub-tropical climate with very hot summers and moderately cold winters. The maximum temperature recorded during summer is 45°C (in the month of June), while the lowest temperature recorded (in January) is 4°C. The average annual rainfall in the area is 794 mm of which 80% is received from the southwest monsoon during the months of July to September.

2.1 *Geological setting*

The study area is a part of the central Ganga Plain and the Delhi Supergroups form its basement

(Kumar 2005). The Delhi Quartzite, in turn, is overlain by Quaternary alluvium with a total thickness of approximately 1.3 km (Singh 2004; Khan 2005).

The alluvial deposits can be subdivided into older and younger alluvium. The latter is confined to river channels and the vicinity of the lowland areas. It is generally inundated by floods during the monsoon.

The alluvium in the Kali–Hindon interfluve region consists of alternate beds of sand and clay with occasional interbeds of calcareous concretions (i.e., *Kankar*). The granular zones consist of various sand grades varying from fine through medium to coarse sands.

2.2 *Hydrogeological framework*

Four distinct permeable granular zones occur within a depth of 450 m bgl (i.e., below ground level), separated by three distinct impermeable horizons. The granular zones lie in depth ranges of 1–185 m, 115–235 m, 235–329 m and 355–488 m bgl (Bhatnagar *et al* 1982).

The ground elevation varies from 245 metres above mean sea level (m amsl) in the north to 230 m amsl in the southern part of the study area (figure 1).

In the present investigation the first aquifer was studied in detail. The hydrogeological cross-section drawn along A–B in the northern part of the basin (figure 2a) shows the occurrence of three granular zones. The top clay layer is persistent throughout, though it varies in thickness from 6 m in the east to 18 m in the west. The first granular zone lies at a depth of 3 to 9 m bgl. This zone is separated by a clay bed which is 30 m thick in the eastern part from the second granular zone which occurs as a lensoid body within thick clay bed gradually pinching out towards the east. The third aquifer is thick and highly permeable.

The section drawn along line E–F (figure 2b) represents the southern portion of the basin. The top clay layer is missing from eastern and western parts although a thin top clay is present in the central part. The second clay layer is very thick. Two sand lenses occur, one on the western side and a very thin lens in the central part of the section. The third granular zone is highly permeable.

On a regional scale it can be seen that the clay layers are impersistent and to a depth of 185 m the three aquifers can be regarded as a single aquifer body.

The pre-monsoon water level during June 2004 varies between 4.6 and 17.7 metres below ground level (i.e., m bgl). The post-monsoon water level variation during November 2004 was between 3.5 m and 16.5 m bgl respectively. The deeper water levels

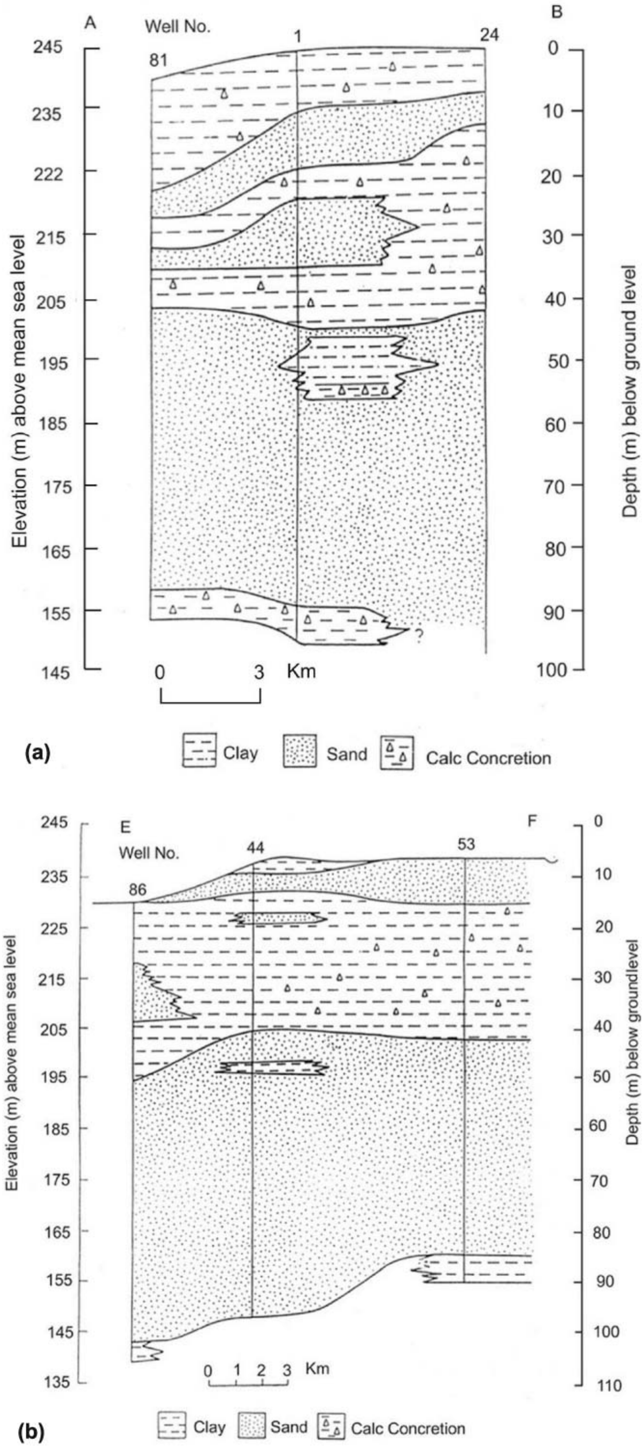

Figure 2. **(a)** Hydrogeological cross section showing vertical and lateral disposition of aquifers along line A–B. **(b)** Hydrogeological cross section showing vertical and lateral disposition of aquifers along line E–F.

were recorded in the southern part of the basin, while the shallow water levels were recorded close to the Kali River. The water table contour map of the study area, based on the data collected in May 2004, shows that the elevation of the water table ranges between 238 metres above mean sea

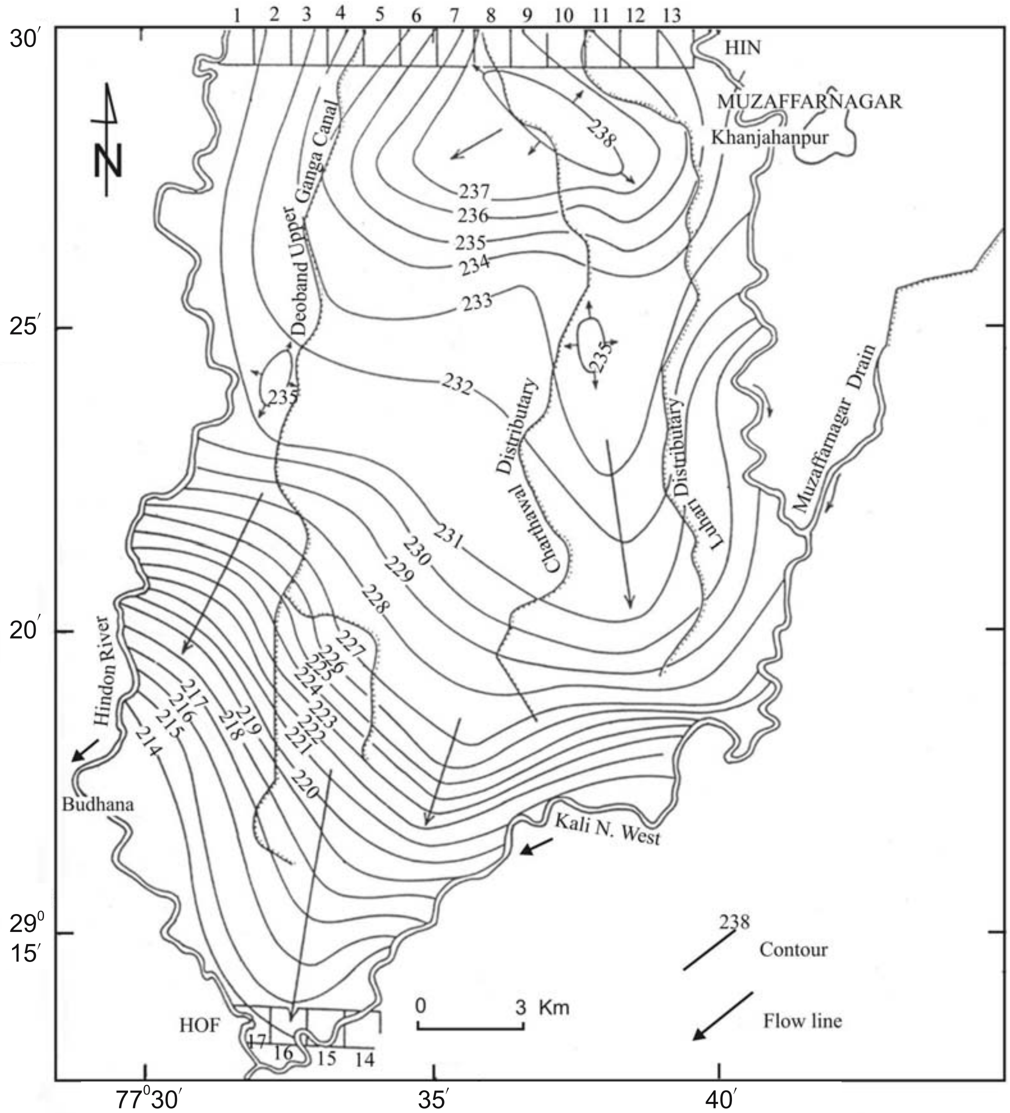

Figure 3. Water table contour map (June 2004) with grid patterns to calculate inflow and outflow components.

level (amsl) in the NE and 215 m amsl in the SW (figure 3). Thus on a regional scale, the groundwater flow direction is generally from north to south.

The hydraulic gradient varies from 0.76 to 4.4 m/km. A distinct feature is that the hydraulic gradient is very steep in southwestern and southeastern parts close to river channels. Both the rivers are effluent in nature. This steep gradient (2.76 to 4.4 m/km) is, in all likelihood, related to over-exploitation of groundwater. A number of groundwater mounds are identified in the area reflecting the contribution of surface waters to groundwater through canal seepages and irrigation return flows. The permeability of the regional aquifer is between 25 and 30 m/day.

Water table depth fluctuation was prepared for eight successive years (1998–2005) for two permanent hydrograph stations. These graphs show a declining trend (figure 4). A trend line was fitted on both the graphs. Using 't' statistics for testing significance of observed regression coefficient, the values of R^2 and R for the given data set varies between 0.53–0.44 and 0.73–0.66 for Shahpur and Baghra stations, respectively. Both the values are in the significance level of 0.01 which is quite good fitting with 99% of confidence. The rate of water level decline is 0.46 m/year at Shahpur and 0.48 m/year at Baghra.

3. Recharge to groundwater

The inflow components are positive and contribute to the recharge of the aquifer. Study of natural groundwater recharge due to direct infiltration of rainfall is a basic requirement in any water balance study. Recharge due to irrigation return flow, canal

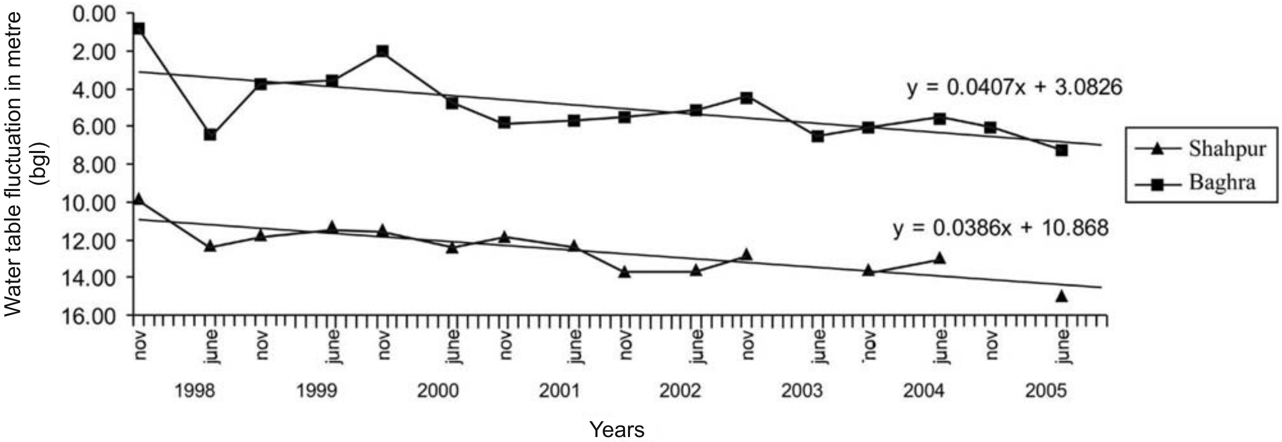

Figure 4. Water table fluctuation graphs showing long term declining trend.

seepage, and horizontal subsurface inflow components were also analysed and calculated.

3.1 *Natural groundwater recharge* (R_R)

3.1a Monsoon rainfall recharge (R_M)

The monsoon rainfall recharge corresponds to water table fluctuation starting from the period just before and after the onset of monsoon. Accurate water level data in the basin allows the estimation of the infiltration using basic relationship between balance over a given period and resulting water level fluctuations (Healy and Cook 2002).

A detailed monitoring of water level in 32 observation wells evenly spaced in the area was carried out in June and November 2004. The recharge was calculated by water table fluctuation (WTF) and tritium method for the year 2004. The geographical area (A) is 395 km^2. On the basis of the monitoring data an average value of water level fluctuation (Δh) i.e., 0.75 m is taken for recharge calculation. The specific yield (S_y) is taken as 0.15.

$$\mathrm{WTF} = A \times S_Y \times \Delta h$$

$$\mathrm{WTF} = 44.43 \qquad \text{million cubic metres (Mcum)}$$

$$\mathrm{WTF} = R_M = 44.43 \text{ Mcum.}$$

3.1b Non-monsoon rainfall recharge (R_{NM})

The non-monsoon rainfall recharge (R_{NM}) is calculated by applying infiltration factor to the rainfall.

$$R_{NM} = \text{Geographical Area} \times \text{Non-monsoon Rainfall} \times \text{Infiltration Factor}$$

where geographical area is 395 km^2, 0.1492 is the non-monsoon rainfall in metres for the year 2004 and 0.25 is the infiltration factor (Khan 1992).

$$R_{NM} = 395 \times 10^6 \times 0.1492 \times 0.25$$

$$R_{NM} = 14.7 \text{ Mcum}$$

$$\text{Total Recharge} = (R_M) + (R_{NM})$$

$$\text{Total Recharge} = 44.43 + 14.7 = 59.13 \text{ Mcum.}$$

3.1c Tritium method

A study was carried out using tritium tracer on groundwater recharge in the alluvial deposits of Indo-Gangetic plains of western Uttar Pradesh. Based on this estimation 22% of total rainfall is taken as recharge to aquifer (Goel 1975). The 20% of total rainfall was taken as vertical recharge to aquifer in Daha region adjoining the study area (Gupta *et al* 1979, 1985). This estimate was based on analysis of water level fluctuations and was supported by tritium tracer studies. Since this basin is adjacent to the present study area therefore 20% of rainfall is considered as recharge to aquifer.

Rainfall for the year 2004 = 568.6 mm.

20% of rainfall = 113.72 mm.

Recharge = 44.92 Mcum.

The variation obtained by these two methods is in the order of 20%. Due to the paucity of water level fluctuation data, only tritium method was applied to calculate recharge for 2001, 2002, 2003 and 2005.

3.2 *Inflow from irrigation return flow (IRF)*

To evaluate the recharge from irrigation return flow to the groundwater, 30% of the total volume of

Table 1. *Recharge through irrigation return flow for the year 2004.*

Crop type	Area irrigated (km^2)	Average wetted depth (m)	Irrigation water applied (Mcum)	Seepage factor (%)	Seepage (Mcum)
Monsoon					
Kharif	387.94	0.4	155.17	40	62.07
Non-monsoon					
Rabi	127.5	0.4	51	30	15.3
Zaid	90.6	0.15	13.5	30	4.07

Table 2. *Recharge due to canal seepage for the year 2004.*

Type of canal	Total length of canal (km)	Average wetted perimeter (m)	Average running days		Seepage (Mcum)		Yearly (Mcum)
			Non-monsoon	Monsoon	Non-monsoon [Columns $2 \times 3 \times 4 \times 216 \times 10^{-6}$]	Monsoon [Columns $2 \times 3 \times 5 \times 216 \times 10^{-6}$]	
1	2	3	4	5	6	7	8
Branch	27.5	5.41	182	93	5.85	2.98	
Distributary	44	3.24	107	60	3.3	1.85	16.26
Minor	26.5	2.28	105	70	1.37	0.91	

water applied is assumed to return to groundwater body. The crop-wise return seepage in the basin has been calculated in table 1.

The total quantum of the irrigation return flow for the year 2004 is thus computed to be 81.44 Mcum. The IRF for the year 2001, 2002, 2003 and 2005 was also calculated which comes out 68.4, 80.91, 81.2 and 81.66 Mcum, respectively.

3.3 *Inflow from canal seepage* (C_S)

Recharge through percolation from canals depends on various factors including infiltration capacity of the canal, sub-surface lithology, extent of wetted perimeter, length of canal (Karanth 1987). The seepages from various canals and distributaries are tabulated in table 2.

The total recharge due to canal seepage (C_S) for 2004 is estimated to be 16.26 Mcum. Canal seepage for the year 2001, 2002, 2003 and 2005 is considered uniform since little variation is observed in total number of running days.

3.4 *Horizontal flow across the boundaries of the basin* (Q_{INF}) *– 2004*

The Kali and Hindon rivers may be regarded as hydraulically connected with the aquifer. The water table contour maps show the effluent nature of these rivers. The horizontal inflow was calculated from northern part of the basin (figure 3) which is as follows:

These flows are dependent on horizontal permeability, thickness of the saturated zone and local hydraulic gradient.

$$Q_{\text{INF}} = T \times \left(\frac{\Delta h}{\Delta l}\right) \times \Delta w$$

where, Q_{INF} is the total inflow towards the study area, T is the transmissivity (m^2/day), $(\Delta h/\Delta l)$ is the hydraulic gradient, and Δw is the width of the grid (m).

Applying and solving the above equation for each grid of uniform length and breadth,

$$Q_{\text{INF}} = \sum_{i=1}^{13} Q_i = \sum_{i=1}^{13} T_i \times \frac{\Delta h_i}{\Delta l} \times \Delta w$$

$$= \frac{\Delta w}{\Delta l} \sum_{i=1}^{13} T_i \times \Delta h_i$$

where $T_{i=1,6} = 1108\,\text{m}^2/\text{day}$; $T_{i=7,13} = 769\,\text{m}^2/\text{day}$ and Δh_i refers to the change in hydraulic head at each grid.

$$Q_{\text{INF}} = \sum_{i=1}^{13} Q_i = 6.1\,\text{Mcum}.$$

The inflows component for the year 2001, 2002, 2003 and 2005 is taken as the same as that of the year 2004 since the hydraulic characteristics do not change significantly during these years.

4. Total recharge (R_T)

The gross groundwater recharge is approximated by summing up the values obtained for groundwater recharge, canal seepage, irrigation return flow and horizontal inflow, i.e.,

$$R_T = R_R + IRF + C_S + Q_{\text{INF}}$$

$$R_T = 44.92 + 81.44 + 16.26 + 6.1 = 148.72\,\text{Mcum}.$$

5. Groundwater draft

Groundwater discharge through pumpage is the major negative component (i.e., outflows) in the irrigated lands. Discharge mainly takes place through pumpage by various groundwater structures. Evaporation from the water table and subsurface horizontal outflows also contributes besides groundwater flowing to the bounding Kali and Hindon rivers. However, the base flows into rivers are assumed negligible and are not taken into consideration in this study.

5.1 *Abstraction by pumping for the year 2004 (D_P)*

In the study area, there are 50 state tube wells, 6090 private tube wells, and 3110 pumping sets in the year 2004. Initially, the unit annual discharge rates for state tube wells, private tube wells and pumping sets were given approximately as 0.18, 0.02 and 0.014 Mcum/year, respectively (Khan 1992).

The groundwater draft has been computed by multiplying the total number of wells by unit annual discharge rate. The unit annual discharge is worked out for 329 days. Groundwater abstraction is considered nil during the 36 rainy days. Therefore the total annual discharge through pumping (D_P) comes out to be 156.91 Mcum. Based on tubewell census, the draft through pumpage for the year 2001, 2002, 2003 and 2005 was calculated which comes out 161.83, 159.99, 157.53 and 158.82 Mcum respectively.

5.2 *Evaporation from groundwater table (EVAP) – 2004*

This component is evaluated using the relation

$$\text{EVAP} = 7.19(z)^{-1.49}$$

where z is the average water table depth from soil in metre.

Evaporation flux is expressed as an inverse power function of the depth to water table below the soil surface, independent of the soil characteristics (Coudrain–Ribsten *et al* 1998). The average depth to water table within the study area is assumed to be 7 metres.

$$\text{EVAP} = 7.19(7)^{-1.49}$$

$$\text{EVAP} = 1.56\,\text{Mcum}.$$

The EVAP component is taken 1.56 Mcum/year for calculation of water balance (draft) in the rest of the years.

5.3 *Groundwater horizontal outflow (H_{OUT}) – 2004*

The groundwater draft through horizontal outflow component (H_{OUT}) estimated in the similar manner as that of Q_{INF}.

$$Q_{\text{OUT}} = T \times \frac{\mathrm{d}h}{\mathrm{d}l} \times \mathrm{d}w$$

$$Q_{\text{OUT}} = \sum_{i=14}^{17} Q_i = \sum_{i=14}^{17} T_i \times \frac{\Delta h_i}{\Delta l} \times \Delta w$$

$$= \frac{\Delta w}{\Delta l} \sum_{i=14}^{17} T_i \times \Delta h_i$$

where $T_{i=13,17} = 974\,\text{m}^2/\text{day}$ is the transmissivity values at respective grid.

$$Q_{\text{OUT}} = 2.6\,\text{Mcum}.$$

6. Total draft (D_T)

The value of total draft is calculated by summing up draft through pumping from wells of all types, losses via evaporation losses and horizontal subsurface outflows.

$$D_T = D_P + \text{EVAP} + Q_{\text{OUT}}$$

$$D_T = 156.91 + 1.56 + 2.59 = 161.06\,\text{Mcum}.$$

7. Groundwater budget

The quantitative changes due to the difference between total inflows and total outflows from the aquifer may be expressed in a water balance equation based on law of conservation of mass (Karanth 1987).

The groundwater balance may be expressed in the form of the equation

$$I - O = \pm\Delta S$$

Table 3. *Yearwise groundwater balance.*

Year	Rainfall (mm)	Total recharge (Mcum)	Total discharge (Mcum)	Groundwater storage (ΔS) (Mcum)
2001	733.8	148.74	166.78	−18.04
2002	998.6	182.15	164.15	+18.0
2003	967.2	179.97	161.67	+18.29
2004	568.6	148.72	161.06	−12.34
2005	1242	202.14	162.97	+39.17

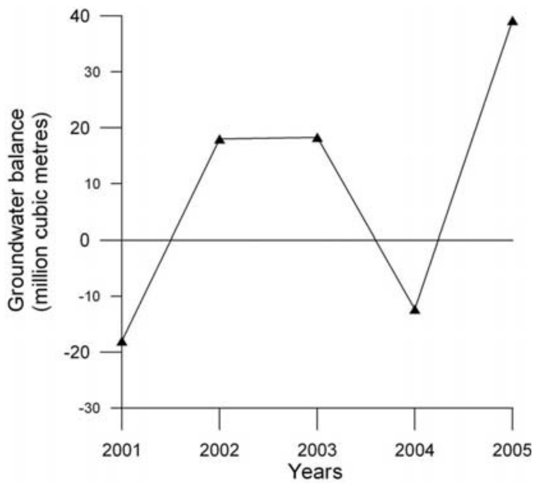

Figure 5. Trends of groundwater balance for the years 2001–2005.

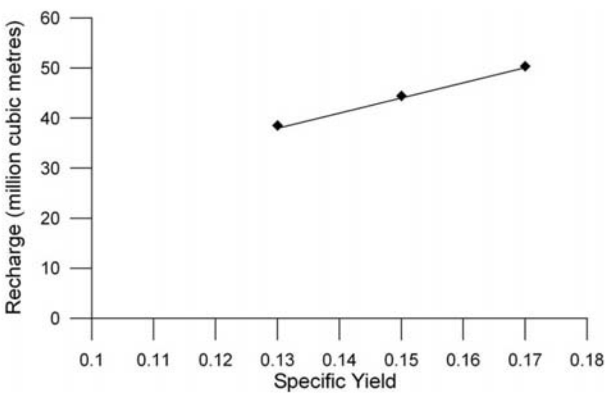

Figure 6. Graphs showing sensitivity of groundwater recharge to specific yield.

where I = inflow, includes all recharge parameters O = outflow, includes all discharge parameters and $\pm\Delta S$ = changes in storage.

Substituting the values derived in the study in the groundwater balance equation gives the following:

$$\Delta S = 148.72 - 161.06$$

$$\Delta S = -12.34\,\text{Mcum}.$$

The balance of −12.34 Mcum/year for the year 2004 indicates that the study area has a negative groundwater balance.

Using the above methodology groundwater balance is calculated for the year 2001, 2002, 2003, and 2005. The results are tabulated in table 3 and shown in figure 5.

8. Sensitivity analysis

Sensitivity analysis helps to understand the significant role played by an individual parameter in the computation of groundwater balance. The principal variable components of groundwater balance, to which the groundwater storage is highly sensitive, are rainfall, specific yield and total number of groundwater draft structures. Among the said parameters, rainfall is the most influential parameter which affects the recharge. The average annual rainfall in the area is 794 mm. A decrease or increase in rainfall affects the groundwater balance substantially. A perusal of table 3 and figure 5 shows that the balance is negative for 2001 and 2004. These years also receive below average rainfall. However, groundwater balance is positive for the year 2002, 2003 and 2005 and the rainfall was above average in these three years. Further, it is concluded that negative balance is not a permanent feature but it is dynamic in nature.

A number of pumping tests were carried out by Central Groundwater Board (CGWB) in the area and its adjoining catchments under the Upper Yamuna Project. The specific yield varied between 0.13 and 0.17 (Bhatnagar *et al* 1982; Khan 1992; Gupta *et al* 1985). However a mean value (0.15) for the specific yield is taken for the present study. An attempt has been made to evaluate the sensitivity of recharge to specific yield. Figure 6 shows variation in recharge with specific yield. An increase by 2% in specific yield increases the recharge by 12%, which can affect the recharge parameter significantly.

The groundwater draft directly corresponds to the number of pumping wells in the area. The number of groundwater draft structures has increased from the year 2001 to 2005 which directly influences the groundwater budget.

9. Conclusions

Knowledge of groundwater balance within a basin is crucial information in order to manage the groundwater resource. This study makes a detailed effort to assess the groundwater budget of the Kali–Hindon inter-stream region. It is very clear from the estimates that the development of groundwater in the region is intense and a slight change in one of the components, e.g., an increase in draft or a decrease in recharge henceforth will seriously deplete the groundwater storage.

It is clear that the situation has reached an alarming stage which is likely to deteriorate further in the coming years. Future deterioration can be expected due to the following factors:

- Unless strictly controlled, groundwater abstraction patterns generally show a year-to-year increase and
- the rainfall value used in the calculation of natural recharge is from the good monsoon year; a small decrease in rainfall or change in rainfall pattern will reduce the recharge component.

It is therefore clear that strict controls on groundwater abstraction need to be introduced in order to manage groundwater resources of the Kali–Hindon inter-stream region. The following remedial measures are suggested:

- *Further groundwater developments*: The water balance calculations indicate that even the present rate of withdrawal may not be sustainable, thus no further groundwater exploitation should be allowed.
- *Controlled abstraction*: In order to reduce total abstraction even the present rate of pumping has to be carefully controlled. For example groundwater withdrawal could be reduced in the south of the region where low aquifer permeability has led to sharp water level declines. It is considered that a slight increase in groundwater withdrawals in the northern part which contains canal networks may not affect the water balance.
- *Augmentation of water resources*: Suitable measures for augmentation of groundwater resources may be adopted e.g., artificial recharge may ease the situation in the southern part before the situation becomes unmanageable.
- *Further scientific investigations*: Several components of the groundwater balance are time-dependent and further scientific investigations (particularly region-wise) are necessary in order to provide the required additional accuracy and precision.
- *Groundwater quality*: It is possible that further pumping may lead to a deterioration of groundwater quality leading to its unsuitability as a drinking water source by the rural population; further groundwater quality investigations are required.
- *River aquifer interaction*: The imbalance of groundwater may also affect the nature of river and aquifer interaction and they may both get changed resulting in ecological problems.

Acknowledgements

The authors are grateful to the Chairman of the Department of Geology for providing facilities to carry out this work. Discussions with the scientists of Bureau de Recherches Geologiques et Minieres (BRGM), France at the Indo-French Centre for Groundwater Research, Hyderabad have been very useful in incorporating new approaches to the study. The authors are also thankful to Mr. Alan Rendell, Principal Hydrogeologist (Retd.), Mott MacDonald International Cambridge, UK for his suggestions which improved the manuscript.

References

Bhatnagar N C, Agashe R M and Sikka V M 1982 "Parameter Determination of Aquifer System", Water Balance Study of Upper Yamuna Basin, Section – Geohydrology, Tech. Rep. No. 9, Upper Yamuna Project, C.G.W.B., N.W. Region, Chandigarh, India.

Coudrain-Ribsten A, Pratx B, Talbi A and Jusserand C 1998 Is the evaporation from Pheratic aquifers in arid zones independent of the soil characteristics. C.R. Acad Sci. Paris. Sciences de la Terre et des Planets, France, **326** 159–165.

Earth Summit 1992 Agenda 21 programme of action of Sustainable Development, UNCED, Rio de Janeiro, Brazil, 174–175.

Goel P S 1975 Tritium Tracer Studies on Groundwater Recharge in the Alluvial Deposits of Indo-Gangetic Plains of Western U.P., Punjab and Haryana: Approaches and Methodologies for Development of Groundwater Resources. Proc. Indo-German Workshop, Hyderabad, India, 319–322.

Gupta C P, Thangarajan M and Gurunadha Rao V V S 1979 Electric Analog model study of aquifer in Krishni–Hindon interstream region, Uttar Pradesh, India; *Ground Water*; **17(3)** 284–292.

Gupta C P, Ahmed S and Gurnadha Rao V V S 1985 Conjunctive utilization of surface and groundwater to arrest the water-level decline in an alluvial aquifer; *J. Hydrol.* **76(3/4)** 351–361.

Healy R W and Cook P G 2002 Using groundwater levels to estimate recharge; *J. Hydrogeol.* **10** 91–109.

Karanth K R 1987 Groundwater Assessment, Development and Management (New Delhi: Tata McGraw Hill Publishing) 576–638.

Khan A M 1992 Report on Systematic Hydrogeological Survey in parts of Muzffarnagar District, U.P. Central Groundwater Board, Northern Region, Lucknow, India.

Khan M M A 2005 Hydrogeology and groundwater quality characteristics of Kali–Hindon sub-basin in parts of western U.P. Unpublished M.Phil. Dissertation Aligarh Muslim University, Aligarh, India, 75p.

Kumar G 2005 Geology of Uttranchal and Uttar Pradesh, Geological Society of India, Bangalore.

Kumar S 1994 Report on Hydrogeology and Groundwater Resources Potential, Muzaffarnagar Districts, U.P. Central Groundwater Board, Northern Region, Lucknow, India.

Marechal J C, Galeazzi L and Dewandel B 2002 Consequences of groundwater imbalance in a hard rock watershed: a case study from Andhra Pradesh; Proc. of the Diamond Jubilee Workshop-I. The Water Crisis – Hope and Action for Humanity's Future, November 2002. National Geophysical Research Institute, Hyderabad, India.

Singh I B 2004 Late Quaternary History of the Ganga Plains; *J. Geol. Soc. India* **64** 431–454.

MS received 25 April 2007; revised 5 October 2007; accepted 6 October 2007