Journal of Hydrology: Regional Studies 4 (2015) 212–226

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Groundwater management options in North district of Delhi, India: A groundwater surplus region in over-exploited aquifers

Shashank Shekhar*, Roger S.K. Mao, Esther B. Imchen

Department of Geology, University of Delhi, Delhi 110007, India

ARTICLE INFO

Article history:
Received 1 March 2014
Received in revised form 16 February 2015
Accepted 8 March 2015
Available online 2 April 2015

Keywords:
India
Hydrogeological domain
Groundwater management
Baseflow
Groundwater salinity

ABSTRACT

Study region: North district of Delhi, India.

Study focus: The North district of Delhi has mostly shallow water levels and is a groundwater surplus region in contrast to the over-exploited aquifers of the region. The surface runoff and flood waters during monsoon season in the district either causes water logging in lower elevation areas or they join drains and rivers as rejected recharge. This study aims to understand groundwater dynamics of the region in perspective of the aquifer architecture and proposes groundwater management options to meet local water requirements.

New hydrological insights in the region: Three distinct hydrogeological domains are identified with subtle differences in groundwater occurrence. Insights are obtained in stream–aquifer interaction and baseflow to the Yamuna River is quantified. The salinity enrichment in groundwater has been attributed to water logging in clay rich formations under semi arid condition. The viability of limited dewatering of shallow aquifers and its replenishment by enhanced recharge from surface runoff and flood waters during the monsoon period have been established.

* Corresponding author. Tel.: +91 11 921260038.
E-mail address: shashankshekhar01@gmail.com (S. Shekhar).

http://dx.doi.org/10.1016/j.ejrh.2015.03.003

1. Introduction

The state of Delhi is supplied with around 1066 million m^3/day of potable water against a demand of 1476 million m^3/day (Shekhar and Prasad, 2009). This domestic water requirement is increasing at an exponential rate in tune with the population growth of the city. The deficit in water supply at the level of individuals is met by exploiting easily available groundwater resources. This has lead to over exploitation of groundwater resources in seven out of nine districts in Delhi (Chatterjee et al., 2009). The two districts which do not have overexploited groundwater resources are north and central district (Fig. 1). The groundwater exploitation in central district is 1.65 million m^3 compared to the net groundwater recharge of 1.88 million m^3 (Chatterjee et al., 2009). Hence if groundwater exploitation in the district is increased by small amount, the aquifers would be overexploited. In contrast to all other districts, the groundwater exploitation in north district is 2.55 million m^3 compared to net groundwater recharge of 7.36 million m^3. In perspective of sustainable urban water management strategy in Delhi region, it is proposed that the water requirements of the district could be met by groundwater sources. This would facilitate diversion of treated river water currently being supplied in the district to other water scarce areas of Delhi.

A similar water supply project is operational in Palla well field to the north of the present study area, where a battery of ninety tubewells and Ranney wells in shallow water level areas extract around 41–49 million m^3/year of groundwater. The water augments drinking water supply of Delhi. These exploited aquifers get replenished by recharge during monsoon rains and floods (Shekhar and Rao, 2010).

The north district is one of the highly urbanized districts of Delhi covering an area of 60 km^2 (Fig. 1). The district is for nearly 37% of its area covered by urban paving (roof, road, pavement and other concretized areas) (Chatterjee et al., 2009). Some cultivation is done in parts of the district falling within the active flood plain (Fig. 2). The average annual rainfall is 887 mm (Period 1980–2003) in the district (CGWB, 2006b; Singh et al., 2005). This is highest average annual rainfall for a district in Delhi. Thus the rainfall recharge to groundwater system during monsoon period is 4.89 million m^3, while in non monsoon season it is about 1.23 million m^3 (Chatterjee et al., 2009). The densely vegetated North Delhi ridge (Alwar Quartzite) roughly occupies 3.6 km^2 area and active flood plain of the river Yamuna roughly occupies 17.4 km^2 area (Fig. 2). The older alluvium and fluvioaeolian deposits occupy nearly 39 km^2 in the rest of the district (Fig. 2). The active flood plain of river Yamuna has younger alluvium of recent age underlain by older alluvium. The older alluvium of river Yamuna varies in age from 1.56 to 82.2 thousand years (Sinha et al., 2009). The depth to bed rock map (Fig. 3) and the observations in field hint at the presence of a fault on the western margin of the Alwar quartzite in the district. This is a regional fault extending to other parts of Delhi (Shekhar et al., 2005; Shekhar, 2006d; CGWB, 1996; Shekhar and Sarkar, 2013).

The aquifer parameter values published by different authors for the Hard rock formation (Delhi ridge/Alwar quartzite), the younger and older alluvium are presented in Table 1.

Table 1
Aquifer parameter values.

Aquifer parameter	Hard rock formation (Delhi ridge/Alwar quartzite)	Younger alluvium	Older alluvium
Transmissivity (m^2/day)	8 (Purohit, 2000) 5–135 (Shekhar et al., 2009)	600–2000 (Shekhar et al., 2009)	43 (Purohit, 2000) 130–403 (Shekhar et al., 2009)
Hydraulic conductivity (m/day)	–	9.8–20 (Rao et al., 2007)	9.8 (Rao et al., 2007)
Specific Yield	0.015 (Shekhar, 2006d)	0.2 (Shekhar and Prasad, 2009)	0.1 (Shekhar, 2006d)
Average tubewell yield (m^3/hour) (Shekhar et al., 2009)	2–10	50–180	20–60

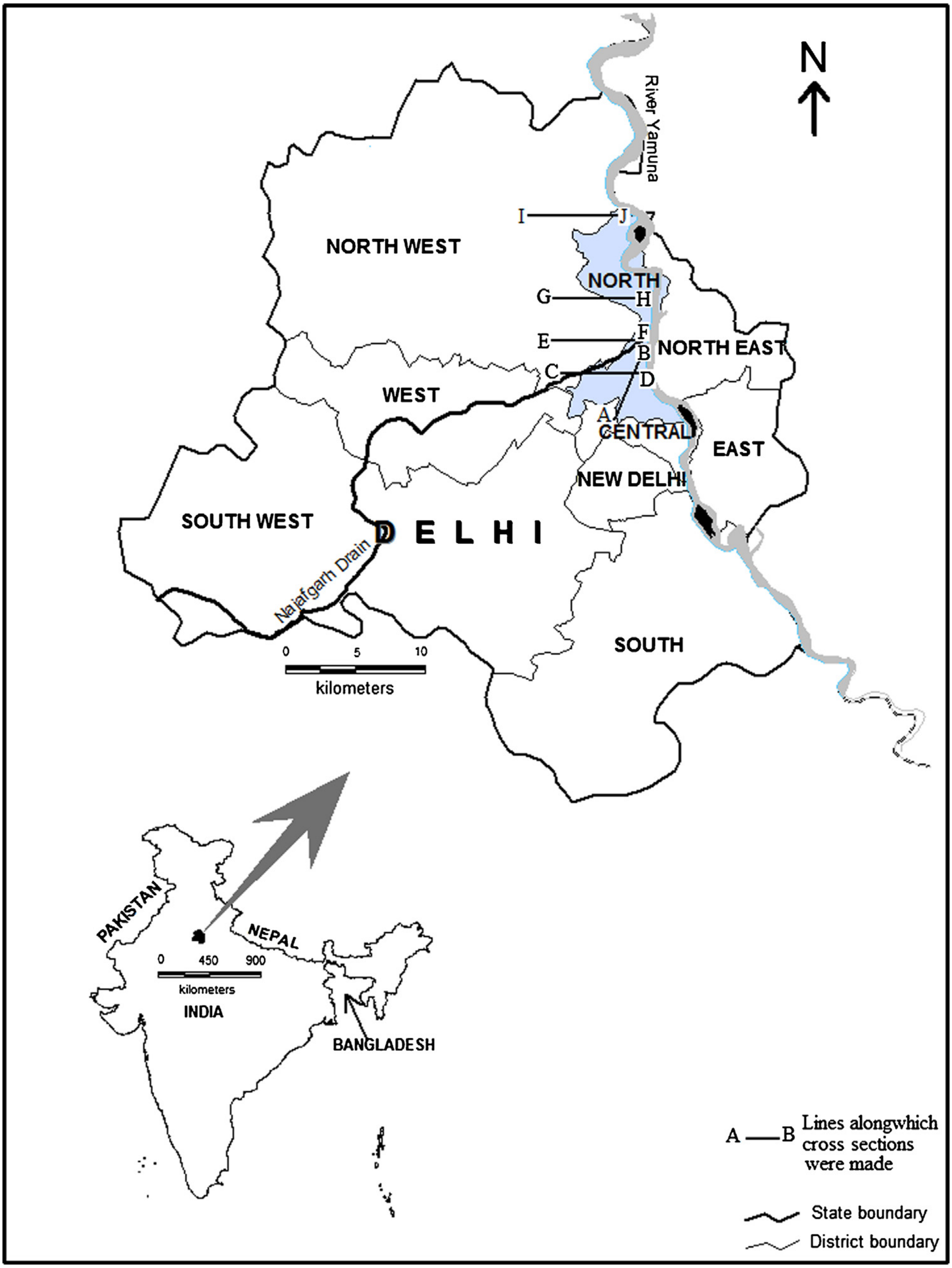

Fig. 1. Location of the North district (blue colored). The lines AB, CD, EF, GH and IJ indicate the lines along which subsurface geological cross-sections have been prepared and shown in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

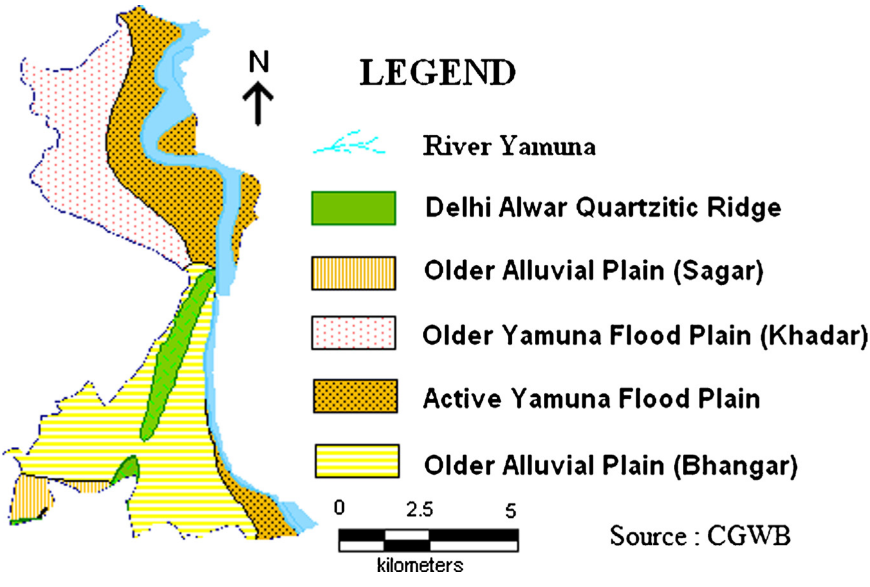

Fig. 2. Geology of the study area.

2. Methodology

The methodology adopted in the present study was to prepare an exhaustive database of the study area by integrating the data collected during field work with the information available from the Central Ground Water Board, Government of India. The data collected during field work consisted of depth to water level data, data related to surface elevation of groundwater monitoring stations above mean sea level and groundwater samples for the estimation of groundwater salinity. Groundwater samples were collected from one hundred stations. The electrical conductivity value of groundwater sample was measured in the field using a pen type EC meter of HACH make. The groundwater samples showing electrical conductivity values of more than 2000 μS/cm were taken to a laboratory where the electrical conductivity value was measured by TDS analyzer (Elico). In addition to this the groundwater quality data from Shekhar (2006a,b) were referred for characterization of salinity variation and delineation of regions with varying level of groundwater salinity.

The surface elevation data was measured with hand held GPS and then corroborated with Google Earth data, available surveyed elevation data, nearest elevation data available on survey sheets, etc. Since the elevation data was only used for estimating water table elevation, the water table contour map prepared from the data was matched with other regional and local water table contours published in CGWB (1996) and CGWB (2006b) before interpretation of the contour maps. It was found that overall the symmetry and gradient of the water table contours was same; hence the map was included for further interpretation. A composite hydrogeological map of the district was prepared in GIS by superposition of a map showing variation in electrical conductivity in the shallow aquifers, depth to water level map, water table contour map and geological map of the district. The subsurface geological cross sections were prepared using borehole litho log data in corroboration with geophysical data.

The groundwater flow to the effluent stretch of Yamuna River for pre monsoon season in the study area was quantified by dividing the area contributing groundwater flow to river Yamuna in to fourteen homogeneous rectangular blocks. Each rectangular block had unique hydraulic gradient and saturated thickness of aquifer contributing groundwater flow in to the river. The average of hydraulic gradient for the years 2005 to 2009 was used and it ranged between 0.002 and 0.009. However no estimation

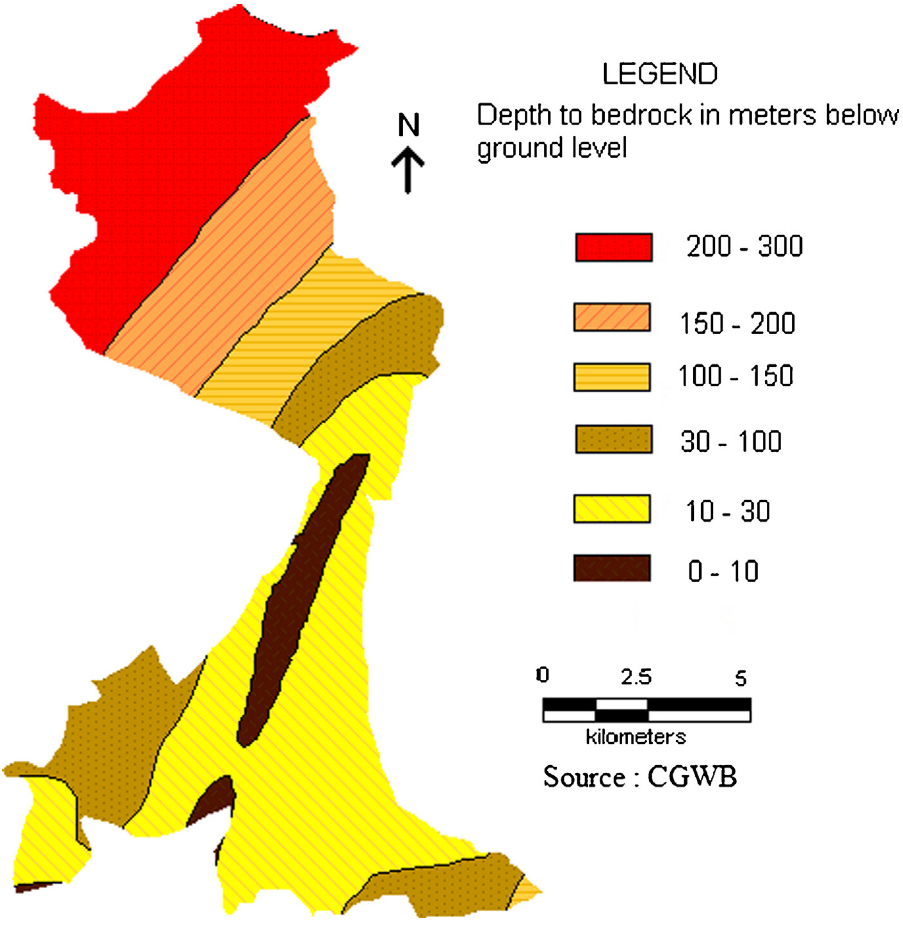

Fig. 3. Variation in depth to basement.

was made for the monsoon months as the river becomes influent. The groundwater flow through each such series of rectangular blocks was calculated using Darcy's equation given as Eq. (1).

$$Q_j = K \times i_j \times A_j \quad (1)$$

where Q_j is volume of groundwater flow per unit time through jth rectangular block. K is hydraulic conductivity of the formation in the rectangular block. i_j is hydraulic gradient in the jth rectangular block. A_j is the saturated cross-section area of the aquifer in the jth rectangular block contributing to river flow and

$$A_j = L_j \times T_j$$

where L_j is length of the jth rectangular block along the river bank; T_j is saturated aquifer thickness in the jth rectangular block along the river bank.

The groundwater contribution to river Yamuna from the study area in its effluent stretch was quantified using Eq. (2).

$$Q(\text{total}) = \sum_{j=1}^{j=n} Q_j \quad (2)$$

where Q(total) is the total groundwater flow to river Yamuna in a given stretch, n is the number of rectangular blocks.

In order to estimate average linear groundwater velocity, the pore water velocity estimated by Sprenger (2011) was used. They had simulated heat transfer in groundwater using temperature gradient to estimate pore water velocity in aquifers of Delhi.

Thus the average linear velocity of groundwater was estimated from pore water velocity using Eq. (3).

$$V_{\text{avg}} = V_p \times \left(\frac{n}{e}\right) \tag{3}$$

where V_{avg} is average groundwater velocity; V_p is pore water velocity; n is porosity; e is effective porosity.

Where the Darcy's law was used to establish the relationship between average groundwater velocity and hydraulic gradient using Eq. (4).

$$V_{\text{avg}} = \left(\frac{K}{e}\right) \times i \tag{4}$$

where K is hydraulic conductivity; e is effective porosity; i is hydraulic gradient.

Thus velocity is directly proportional to hydraulic gradient.

The volumetric estimate of groundwater recharge in shallow water level areas of the Yamuna flood plain and groundwater extraction was done using water level fluctuation data with help of Eq. (5).

$$W = F \times A \times S_y \tag{5}$$

where W is volume of groundwater recharged or extracted; F is water level fluctuations; A is area; S_y is specific yield.

The total monsoon and non monsoon annual recharge to groundwater referred to as annually replenishable dynamic groundwater resource (W) in areas of the district except for the shallow water level area was estimated (GEC, 1997; Shekhar, 2006a,b; Chatterjee et al., 2009) using Eq. (6).

$$W = R_m + R_n \tag{6}$$

where W is total recharge to groundwater. R_m is total monsoon recharge to groundwater. R_n is total non monsoon recharge to groundwater.

The total monsoon recharge to groundwater (R_m) was estimated using Eq. (7).

$$R_m = R_{rm} + R_{om} \tag{7}$$

where R_{rm} is recharge from rainfall during monsoon. R_{om} is recharge from other sources like canal seepage, seepage from ponds etc. during monsoon.

The total non monsoon recharge to groundwater (R_n) was estimated using Eq. (8).

$$R_n = R_{rn} + R_{on} \tag{8}$$

where R_{rn} is recharge from rainfall during non monsoon. R_{on} is recharge from other sources like canal seepage, seepage from ponds etc. during non monsoon.

The recharge from rainfall (R_r) during monsoon and non monsoon season was estimated using Eq. (9).

$$R_r = f \times A \times r_f \tag{9}$$

where f is rainfall infiltration factor; A is area under consideration; R_f is the average rainfall in the season

The net annual groundwater availability (N_{Gw}) was calculated using Eq. (10)

$$N_{Gw} = W - d \tag{10}$$

where d is natural discharge.

The rainfall infiltration factor is based on GEC (1997) norms evolved through case studies on rainfall–recharge relationship. The rainfall infiltration factor for flat bare ground was taken in the

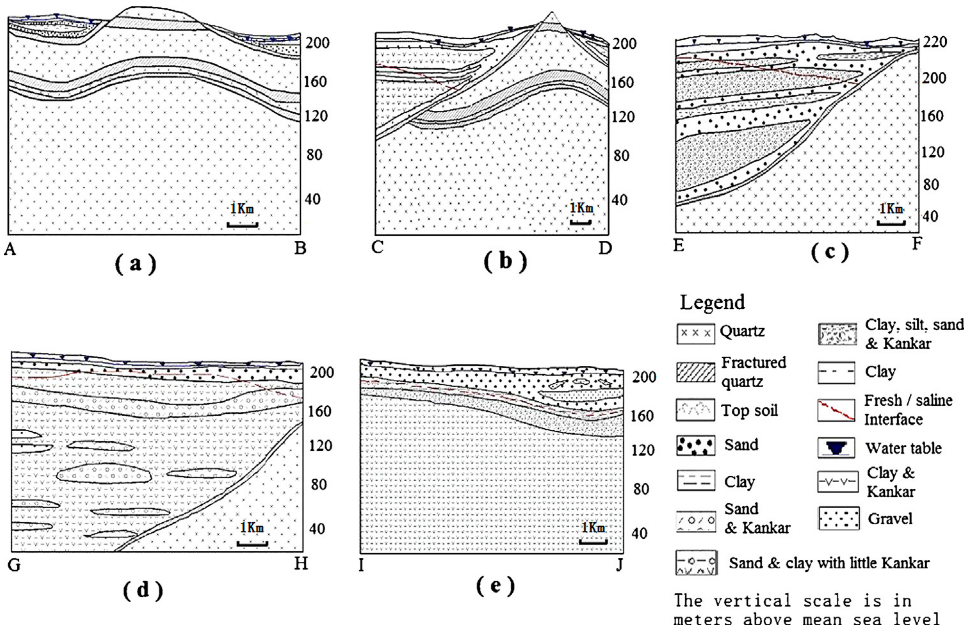

Fig. 4. (a) Subsurface geological cross-section along line AB marked in Fig. 1. (b) Subsurface geological cross-section along line CD marked in Fig. 1. (c) Subsurface geological cross-section along line EF marked in Fig. 1. (d) Subsurface geological cross-section along line GH marked in Fig. 1. (e) Subsurface geological cross-section along line IJ marked in Fig. 1.

range of 0.80 and 0.95 and it varied from 0.5 to 0.15 for the urban paving (Chatterjee et al., 2009). Similarly natural discharge in Eq. (10) refers to groundwater discharge to lakes, ponds, wetlands, through transpiration etc. This is also based on GEC (1997) norms finalized on the basis of case studies. The extent of groundwater development (S_d) was calculated using Eq. (11).

$$S_d = \left(\frac{D_t}{N_{Gw}}\right) \times 100 \qquad (11)$$

where D_t = total annual groundwater draft.

3. Results

3.1. Groundwater occurrence in the district

The groundwater in North district occurs in hardrock areas, fluvioaeolian and alluvium deposits. The younger alluvium in the Yamuna flood plain of Delhi has been classified as unconfined aquifers (CGWB, 1996; Shekhar, 2006c; Rao et al., 2007). The aquifer geometry in the study area was ascertained by a series of cross-sections discussed below.

The geological cross-section (Fig. 4(a)) along AB (Fig. 1) reveals that the basement is overlain by fine to coarse sand with lenses of clay and kankar (local term for small calcareous concretions mixed with some small gravel). The cross-section of Fig. 4(b) along CD (Fig. 1) shows that the basement rock is overlain by coarse sand alternating with clay zone and relatively thicker zone of clay and kankar. Along cross-section EF (Fig. 4(c)) the basement is overlain by a sandy aquifer, alternating with clay, silt, sand layers and clay mixed with kankar layers. Cross-section GH (Fig. 4(d)) shows that the basement quartzite is overlain by a thick layer of clay and kankar with sporadic occurrence of elongated lenses of sand and kankar. The sandy aquifers are found at shallow depth and in the depth range of 30–50 m below ground level (mbgl). The shallow aquifers along cross-section IJ (Fig. 4(e)) are made up of fine

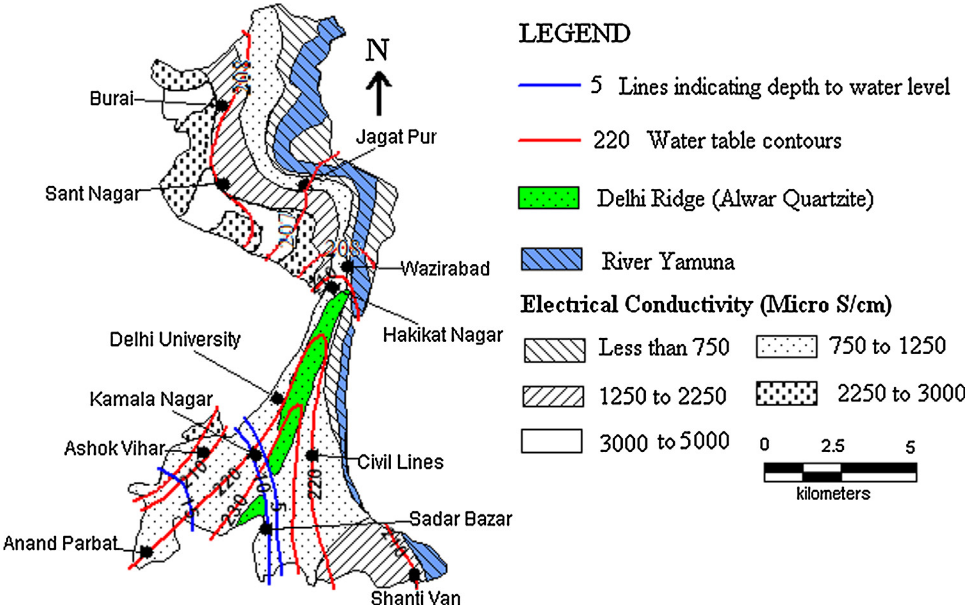

Fig. 5. Hydrogeological map of the study area.

to coarse sand with lenses of gravels. The sand content in the formation decreases with increasing depth and the lowermost unit is composed of clay and kankar.

The average depth to water level in the district shows wide variation from 3 to nearly 20 meters below ground level (mbgl) (Fig. 5). The major portion of the district has depth to water level in the range of 2–5 mbgl. It is only in the south west corner that the deeper water levels are found (Fig. 5). The groundwater level data indicates that a major portion of the district in the northern and eastern part shows post monsoon rise in the water level in the range of 0–0.5 m (Fig. 5). All along north Delhi ridge post monsoon rise in the water level is in the range of 1–2 m. While in the western and south western part of the district post monsoon rise in the water level is in the range of 0.5–1.0 m.

The north Delhi ridge acts as a hydraulic boundary and groundwater flows from it in east and west direction and along the ridge groundwater flows from SW to NE (Fig. 5). Hence the groundwater regime to the east of the ridge in the areas between ridge and river Yamuna are distinct from the groundwater regime to the west of the ridge.

3.2. *Groundwater quality*

The groundwater quality in the district shows defined horizontal and vertical variation in space, especially with regards to salinity. It is clearly observed in Fig. 6 that the depth to fresh/saline interface in groundwater of the district is minimum in the north western part (less than 30 mbgl) and maximum in the south eastern part of the district (50–70 mbgl). The shallow aquifers of the district show increase in salinity toward the west and south eastern part of the district (Fig. 5). The salinity variation in the district revealed that the localities showing high salinity in groundwater are water logged areas, have a predominance of clay rich formations, lower topographic elevation and are groundwater discharge zones. These higher salinity areas have minimal groundwater movement and the stagnant groundwater reacts with the clay materials resulting in the enrichment of salinity in the groundwater of these regions. In other areas of Delhi and adjacent regions, such occurrence of higher salinity in groundwater has been attributed to improper flushing (Shekhar et al., 2005; Lorenzen et al., 2012). Alternatively in semi-arid climatic condition of the area repeated evaporation during peak summer and subsequent dilution during monsoon rains could be leading to leaching of salts in groundwater

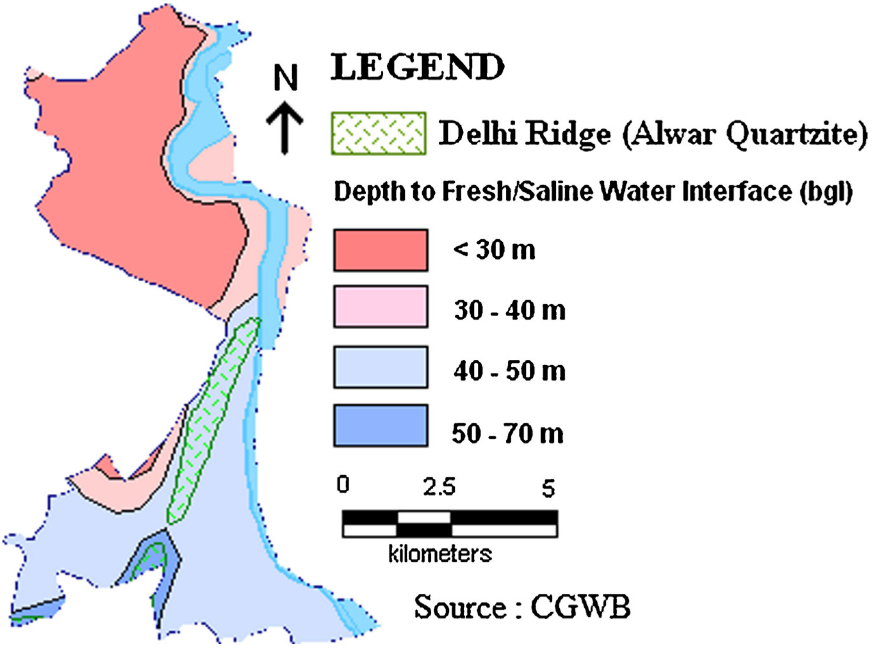

Fig. 6. Variation in depth to fresh/saline interface of groundwater in the district.

thereby enriching salinity of soil and groundwater. Lorenzen et al. (2012) had similar observations on salinity enrichment in alluvial plains of western Delhi and adjacent Haryana. The other major chemical constituents of fresh groundwater in the district are mostly within the permissible limit prescribed for drinking purposes (BIS, 2003). There are a few exceptions like Shekhar (2006a,b) mentions that average concentration of fluoride in groundwater of the district ranges from 0.5 to 1.3 mg/L except three sampling locations of Jagatpur, Ashok Vihar and Inter State Bus Terminal near Shantivan (Fig. 5) where concentration of fluoride in the groundwater is beyond permissible limit of 1.5 mg/L (BIS, 2003). Shekhar (2006a,b) mentions that concentration of nitrate in the groundwater samples collected from the district showed values in the range of 0–89 mg/L. Sarkar and Shekhar (2013) reported arsenic in thirteen groundwater samples from the study area. They reported four samples having arsenic concentrations beyond 0.01 mg/L.

3.3. Groundwater availability in the district

The dynamic groundwater resource assessment for the district was based on the GEC (1997) methodology. The methodology excludes steeply sloping areas and waterlogged shallow water level areas (mostly flood plain and some other areas in the district) from assessment. As the steeply sloping and water logged areas are less likely to have any natural groundwater recharge; the assessment of total annual recharge for these areas is excluded. For estimating recharge from canal seepage, the seepage factor of 0.03 m^3/day for each sq. m wetted area of lined canal was used. While for recharge from water bodies seepage factor of 0.00000014 m/day for each square meter of water spread area was used (after Chatterjee et al., 2009).

The total rainfall recharge (6.12 MCM) for both monsoon season (4.89 MCM) and non monsoon season (1.23 MCM) was estimated using Eq. (9) (Chatterjee et al., 2009) (Table 2). The total recharge from canal seepage (1.94 MCM) for both monsoon season (0.64 MCM) and non monsoon season (1.3 MCM) was estimated using the above mentioned seepage factor (Table 2). Similarly the total recharge from

Table 2
Recharge from different sources in the district.

Recharge during monsoon (MCM)				Recharge during non monsoon (MCM)				Total annual recharge (MCM)
Rainfall	Canal seepage	Water conservation structures	Total monsoon recharge	Rainfall	Canal seepage	Water conservation structures	Total non monsoon recharge	
4.89	0.64	0.09	5.62	1.23	1.3	0.02	2.55	8.17

Source of data: Shekhar (2006a,b), CGWB (2006a), Chatterjee et al. (2009).

Table 3
Annually replenishable groundwater resources in the district.

Annual groundwater recharge	Natural discharge	Net groundwater availability	Annual groundwater draft	Extent of groundwater development
MCM	MCM	MCM	MCM	
8.17	0.817	7.36	2.545	35%

Source of data: Shekhar (2006a,b), CGWB (2006a), Chatterjee et al. (2009).

water conservation structures (0.11 MCM) for both monsoon season (0.09 MCM) and non monsoon season (0.02 MCM) was estimated using the seepage factors mentioned above (Table 2).

The total annual recharge to groundwater was estimated at 8.17 MCM using Eq. (6). It was quantified as sum of total monsoon recharge (5.62 MCM) and total non monsoon recharge (2.55 MCM) estimated using Eqs. (7) and (8) respectively. The net annual groundwater resource in the district was estimated at 7.36 MCM using Eq. (10). For arriving at this figure the 'natural discharge during non monsoon' factor of Eq. (10) was taken as 10 percentage of total recharge to groundwater based on field condition and GEC (1997) norms. The extent of groundwater development was estimated as 35% using Eq. (11) (Table 3). With regards to long term water level trends there has not been significant pre and post monsoon decline in the district and as such it is categorized as "safe category". The district has better groundwater potential in comparisons to groundwater scarce Delhi. This low extent of groundwater development in the district is mainly attributed to the presence of a recharge zone in the form of Delhi ridge through median part of the district and river Yamuna on the eastern fringe of the district. Moreover the district is well supplied with surface water sources for various uses by the residents and major part of the district has comparatively shallow groundwater level.

3.4. *Baseflow and surface-groundwater interaction along Yamuna River*

The Yamuna River flows from north to south. The stream–aquifer interaction shows distinct variation along the stretch of the Yamuna River in the study area. They can be categorized in to distinct segments as below:

3.4.1. *The stretch till Jagatpur (Fig. 5)*

In this stretch the regional water table slope is toward river and groundwater seems to be contributing to river on its right bank. However the hydraulic gradient is much lower compared to the stretch downstream of Wazirabad (Fig. 5). The river bottom elevation in Jagatpur was estimated at 190 meters above mean sea level (Mamsl), while the average water table elevation at about 1.5 km from the river was estimated at 208 meters above mean sea level. The average saturated aquifer thickness contributing groundwater flow to Yamuna River in this stretch was estimated at 18 m. The groundwater contribution to Yamuna River from this stretch of the study area was quantified using Eq. (2). It was estimated that approximately total non monsoon (November to June of next year) baseflow contribution to the Yamuna River from this stretch of the study area was 1.4 MCM/yr. This is quite small compared to average non monsoon discharge of 440 MCM/yr flow through river Yamuna (Soni et al., 2014).

3.4.2. The stretch of the river from Jagatpur to Wazirabad (Fig. 5)

In this stretch the water table gradient indicates toward some amount of seepage of river water in to groundwater system establishing influent nature of the stream. In general in this stretch the water level in the river is above the groundwater levels (Fig. 3, Kumar et al., 2009). This could also be on account of surface water pondage in the Wazirabad barrage.

3.4.3. Stretch of the river downstream of Wazirabad to Shantivan (Fig. 5)

This stretch of the river has mostly water discharged by major drains like Najafgarh and supplementary drains. Sandhu et al. (2011) mention that generally no water is released downstream of Wazirabad Barrage during the dry season. The average channel bottom elevation of River Yamuna in this stretch (downstream of Wazirabad to Shantivan) was estimated after Vijay et al. (2007) as 200 Mamsl, while the average water table elevation near the bank of the river is about 213 Mamsl. With an average saturated aquifer thickness of 13 m the groundwater contribution to the river was quantified as approximately 0.011 MCM/day (2.7 MCM/yr) during the non-monsoon season. Since the area is a shallow water level area, and the hydraulic gradient is low, the groundwater contribution to River Yamuna from the study area which lies on its right bank is very low. Downstream of Wazirabad, the river flow is mainly maintained by discharge from city drains like Najafgarh drain etc. The sewage discharge into River Yamuna in the stretch of the study area is approximately 1.5 MCM/day (548 MCM/annum) (NEERI, 2002). Hence, baseflow from this stretch is very low compared to the total contribution by city drains to River Yamuna.

4. Groundwater management options

The north district of Delhi is a small district comprising of hard rock area in the median part and flood plain of river Yamuna in the eastern part (Fig. 2). The annual groundwater draft is only 2.545 MCM and the net groundwater availability is 7.36 MCM (Table 3). Thus there is additional annual increment in groundwater resources by about 4.81 MCM by annual groundwater recharge through different processes. The groundwater management option for the district should be aimed at optimization of the groundwater resources on the theme of sustainable development. Utilization of groundwater to certain extent is desirable. It prevents water logging in shallow water level areas, soil salinity and groundwater salinity. Continuous flushing of the aquifer by groundwater also prevents salinity enrichment of the groundwater. Thus creating additional limited subsurface storage space in shallow water level areas during premonsoon times and replenishment of the storage space during monsoon times would be desirable. This will lead to augmentation of annually replenishable groundwater resources in the district. The groundwater management option in the district has been discussed by categorizing the district in three distinct hydrogeological domains. This categorization in domains was based on similarity in occurrence and availability of groundwater. This would help the local water supply agency in implementation of schemes. Currently, the water supply is often augmented locally by tubewells at the level of village or colonies. The water management policies discussed further would require small changes in water allocation of treated river water and groundwater. This can be coupled with enhancement of recharge to groundwater. The financial implications would be much less considering sustainability of the management practices and non tangible environmental benefits. The groundwater development and management options for the three hydrogeological domains in the district are discussed below:

4.1. Groundwater development and management in the active Yamuna flood plain

The district has 17.4 km^2 area covered by the active flood plain of River Yamuna (Hydrogeological domain-1 in Fig. 7 and Fig. 2). It has been estimated that approximately 12.6 km^2 area of the active flood plain is north of Wazirabad and 4.8 km^2 is located downstream of Wazirabad. The water storage in Wazirabad barrage has also lead to salinity enrichment in soil and groundwater of closely adjacent areas. Since depth to water level in the area is in range of 5 mbgl, it would be prudent to advocate planned development of groundwater resources in the area of the flood plain upstream of Wazirabad barrage. Shekhar and Prasad (2009) had estimated the average post monsoon water level rise in the

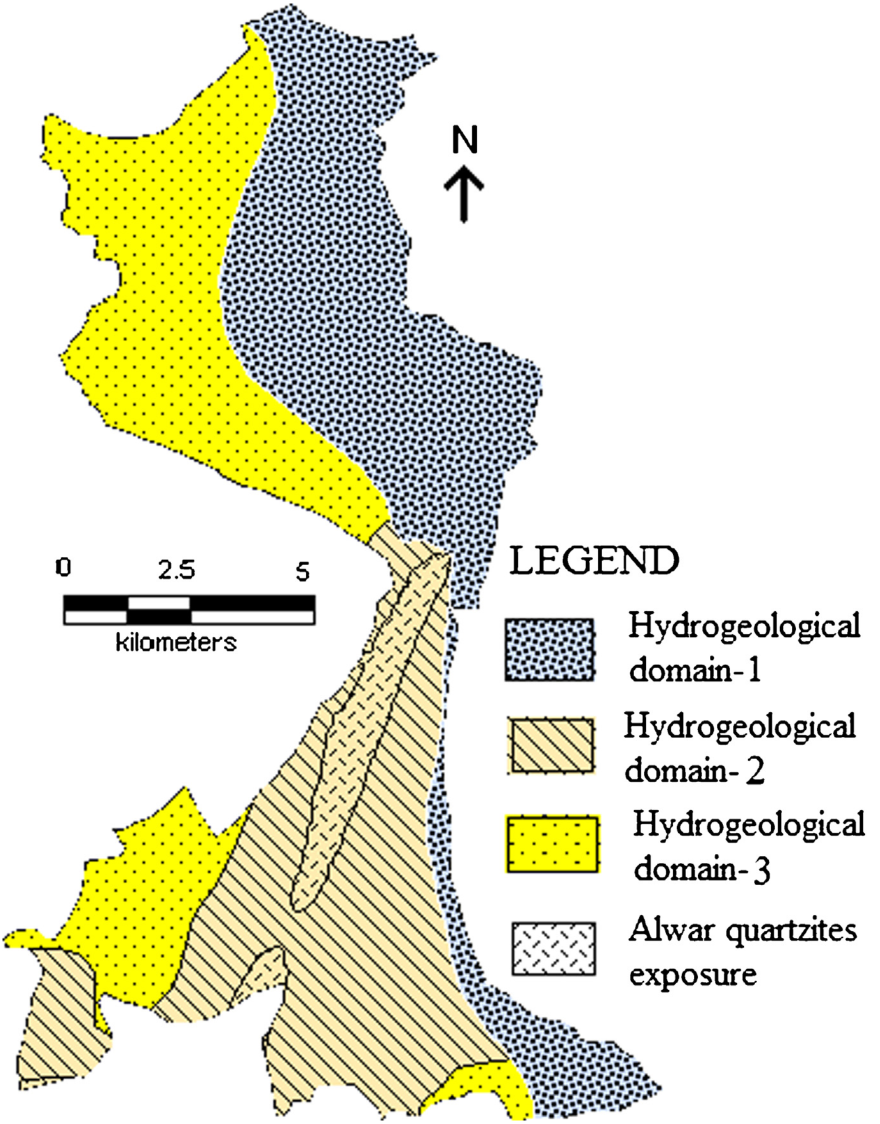

Fig. 7. Derived three distinct hydrogeological domains of the district.

Yamuna flood plain of Delhi as 0.37 m (*F* of Eq. (5)) and specific yield of the formations in the active Yamuna flood plain as 0.2. The annually replenishable groundwater resource in the area of the flood plain upstream of Wazirabad using Eq. (5) was estimated at approximately 1 MCM.

A preliminary estimate made using Eq. (5) establishes that dewatering the flood plain aquifers upstream of Wazirabad by 4 m would yield around 10 MCM of groundwater. Thus the annually replenishable groundwater resources in the area of the flood plain upstream of Wazirabad can be enhanced 10 times by planned groundwater development. Since the area is underlain by saline groundwater, the groundwater pumping must be staggered in space and time as suggested for such areas by Rao et al. (2006, 2007).

The dewatered aquifers of the flood plain can be easily recharged. Since the average pore water velocity (Sprenger, 2011) through aquifers in the flood plain of river Yamuna in the central Delhi stretch is around 0.9 m/day. The average porosity of sand is 40% and it would be reasonable to assume effective porosity as 30%. With this data the average linear groundwater velocity was estimated using Eq. (3) as 1.2 m/day. If we consider that the hydraulic gradient becomes approximately double over the areas which are directly inundated by flood water and the adjacent areas not inundated by flood water, then the groundwater velocity during monsoon floods is estimated using Eq. (4) as 2.4 m/day. With this velocity, over a period of three monsoon months the additional induced groundwater recharge by lateral flow of groundwater from the inundated stretches of the floodplain to stretches not inundated by flood water would be approximately 216 m on either side. In monsoon season the total lateral adjacent stretch on either side of the river inundated by flood water and receiving direct vertical recharge from the flood water would be around 1–2 km. Thus in total the lateral stretch adjacent to river influenced by lateral and vertical groundwater recharge would be around 1.5–2.5 km of the flood plain. Similar estimate was also done by Soni et al. (2014) for estimating groundwater recharge by River Yamuna upstream of the present study area.

In the area downstream of Wazirabad barrage, the active flood plain area available for groundwater development is very small, mostly toward south eastern part of the district (Fig. 2). The Yamuna River is effluent in this stretch. The areas are already occupied by parks with groundwater abstraction for horticulture. Thus the additional groundwater development potential in this stretch was not estimated.

4.2. Groundwater development and management in hard rock and areas adjacent to it with shallow depth to hard rock basement

There is a prominent hard rock ridge in the district known as north Delhi ridge occupying 3.6 km^2. It is enclosed by areas having shallow depth to hard rock basement in the range of 30 mbgl occupying roughly 15 km^2 (Hydrogeological domain-2 in Figs. 7 and 3). These areas often have deep buried pediment which makes a productive aquifer (Bajpai, 2011). The depth to water level in the north Delhi ridge area is in the range of 5 mbgl. Specific yield of the hard rock formation is 0.015 (Shekhar, 2006d). In this case lowering of water level by 4 meters would yield around 0.22 MCM of fresh water (Eq. (5)).

The area adjacent to hard rock with shallower depth to basement in range of 30 mbgl occupies roughly 15 km^2 (Figs. 2 and 3). The average urban paving in the district is 37% (Chatterjee et al., 2009). Thus out of 15 km^2 area adjacent to hard rock nearly 9.5 km^2 is open area available for groundwater development and recharge. The specific yield of this formation is 0.1 (Shekhar, 2006d). Thus dewatering of the aquifers by 4 meters will yield roughly 3.8 MCM of groundwater. These desaturated aquifers can be replenished by adopting suitable techniques which would enhance recharge by enhanced infiltration. Suitable recharge structures based on local storm water drains could be designed in depressions and quarries. This would certainly augment the groundwater resources. In these areas two types of tubewells could be made, one restricted to the overburden only, tapping granular formations of more than 20 m depth, while in the other the overburden could be cased with blank pipe and borehole made in the hard rock only.

4.3. Groundwater development and management in other older alluvial plain area of the district

The area covered by older alluvial plain of the district except the areas adjacent to hard rock with depth to hard rock less than 30 mbgl is roughly 24 km^2 (Hydrogeological domain-3 in Fig. 7 also see Figs. 2 and 3). Using the average urban paving percentage 15 km^2 is estimated to be open area available for groundwater development and recharge. The specific yield of the formation is 0.1 (Shekhar, 2006d). Thus lowering of water levels by 4 m in 15 km^2 area, using Eq. (5) would yield around 6 MCM of water. This 6 MCM includes both saline and fresh water. A good proportion of the open area roughly 8 km^2 near Burari, Santnagar etc. (Fig. 5) has electrical conductivity of groundwater in the range of 2250–5000 μS/cm (TDS of 1350–3000 mg/L). This leaves only 7 km^2 open area available for fresh/marginal groundwater development. Out of which nearly half is freshwater (electrical conductivity less than 1250 μS/cm) and the other half is marginal quality groundwater (electrical conductivity in the range of 1250–2250 μS/cm). The proportionate division of the total yield from open areas, which is 6 MCM, gives: (1) The saline groundwater resources available from 8 km^2 as 3.2 MCM; (2) Marginal groundwater resources available from 3.5 km^2 as approximately 1.4 MCM; and (3) The fresh groundwater resources available from 3.5 km^2 is approximately 1.4 MCM. The groundwater bearing zones in the alluvial areas are generally found in the depth range of 15–19 and 22–28 mbgl. The depth to fresh/saline interface in the groundwater of the potential alluvium areas are generally in the range of 35–40 mbgl (Fig. 6). It would be advisable to restrict the depth of tubewells in alluvial areas in the range of 30 mbgl.

5. Conclusions

The shallow groundwater levels in the area is on account of: (1) lesser groundwater exploitation; (2) adequate recharge from rainfall and elevated quartzite ridge; and (3) recharge to the Yamuna flood plain aquifers through regular monsoon flooding. The salinity enrichment in groundwater has been attributed to water logging in low lands with subsurface predominance of clay rich formations. The stagnant groundwater reacts with the clay materials resulting in enrichment of salinity in the groundwater of these regions. Alternatively the repeated evaporation and dilution in shallow water level areas of this semi arid region could be leading to leaching of salts in to groundwater thereby enriching salinity of soil and groundwater. It is concluded that with suitable groundwater management practices the district has the following groundwater extraction potential: (1) Additional 15.42 MCM of fresh groundwater potential (about 6 times the present abstraction of ∼2.55 MCM); (2) Saline groundwater potential of 3.2 MCM; and (3) Marginally saline groundwater potential of 1.4 MCM.

The fresh groundwater potential has been identified as: (a) 10 MCM from Yamuna flood plain; (b) 0.22 MCM from hard rock areas; (c) 3.8 MCM from shallow depth to hard rock areas adjacent to the hard rocks; and (d) 1.4 MCM from the rest of the older alluvium formations in the district. The marginally saline and saline groundwater resource potential is mostly restricted to shallow water level areas underlain by older alluvium. The quality of groundwater should be a major consideration before augmenting the drinking water needs by groundwater sources.

Conflict of interest

None declared.

Acknowledgements

Financial support by university of Delhi under “Scheme to strengthen R & D and doctoral research program of the University of Delhi by providing research funds to university faculty”, session 2009–2010, is duly acknowledged. The meticulous review comments by anonymous reviewers and editors of the journal helped in improving the manuscript. Special thank to Prof. Okke Batelaan for meticulous review and corrections.

References

Bajpai, V.N., 2011. Hydrogeological studies in the National Capital Territory of Delhi with reference to land use pattern and effective groundwater management. Proc. Indian Natl. Sci. Acad. 77 (1), 31–49.

BIS, 2003. Indian Standard, Drinking Water Specification (First Revision). Bureau of Indian Standards, Manak Bhawan, 9 Bahadur Shah Zafar Marg, New Delhi 110002.

CGWB, Report 1996. Development and Augmentation of Groundwater Resources in NCT of Delhi. Central Groundwater Board, Ministry of Water Resources, Government of India, New Delhi.

CGWB, Report 2006a. Groundwater Resources of NCT, Delhi. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

CGWB, Report 2006b. Hydrogeological Frame Work and Groundwater Management Plan of NCT Delhi. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

Chatterjee, R., Gupta, B.K., Mohiddin, S.K., Singh, P.N., Shekhar, S., Purohit, R., 2009. Dynamic groundwater resources of National Capital Territory, Delhi: assessment, development and management options. Environ. Earth Sci. J. 59 (3), 669–686.

GEC, Report 1997. Groundwater resource estimation methodology-1997. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

Kumar, M., Ramanathan, A.L., Keshari, A.K., 2009. Understanding the extent of interaction between groundwater and surface water through major ion chemistry and multivariate statistical techniques. Hydrol. Process. 23, 297–310.

Lorenzen, G., Sprenger, C., Baudron, P., Gupta, D., Peckdeger, A., 2012. Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and adjacent territories of Haryana State, India. Hydrol. Process. 26, 2333–2345.

NEERI, Report 2002. Environmental Management Plan for Rejuvenation of River Yamuna. National Environmental Engineering Research Institute, Nagpur, India.

Purohit, R.R., (M.Sc dissertation) 2000. Aquifer Evaluation in Hard Rocks and Adjoining Areas of Delhi Region. University of Delhi, Delhi.

Rao, S.V.N., Kumar, S., Shekhar, S., Chakraborti, D., 2006. Optimum pumping from Skimming Wells. J. Hydrol. Eng. 11, 464–471.

Rao, S.V.N., Kumar, S., Shekhar, S., Sinha, S.K., Manju, S., 2007. Optimal pumping from Skimming Wells from the Yamuna river flood plain in north India. Hydrogeol. J. 15, 1157–1167.

Sandhu, C., Grischek, T., Kumar, P., Ray, C., 2011. Potential for Riverbank filtration in India. Clean Technol. Environ. Policy 13, 295–316.

Sarkar, S., Shekhar, S., 2013. An assessment of groundwater quality of lesser contaminated aquifers in North District of Delhi. Proc. Indian Natl. Sci. Acad. 79 (2), 235–243.

Shekhar, S., Singh, S.B., Romani, S., 2005. The controls to the variation in depth to fresh/saline interface in the Groundwater of South West District, NCT Delhi – a case study. J. Geol. Soc. India 66 (7), 17–20.

Shekhar, S., Report 2006a. Reappraisal Hydrogeological Study in North and North West district of NCT Delhi. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

Shekhar, S., Report 2006b. Hydrogeology of North District NCT Delhi. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

Shekhar, S., 2006c. An approach to interpretation of step drawdown tests. Hydrogeol. J. 14, 1018–1027.

Shekhar, S., 2006d. An approximate projection of availability of the fresh groundwater resources in South West district of NCT Delhi, India – a case study. Hydrogeol. J. 14, 1330–1338.

Shekhar, S., Prasad, R.K., 2009. The groundwater in the Yamuna flood plain of Delhi (India) and the management options. Hydrogeol. J. 17, 1557–1560.

Shekhar, S., Purohit, R., Kaushik, Y.B., 2009. Groundwater management in NCT Delhi. In: Proceedings 5th Asian Regional Conference of Indian National Committee on Irrigation and Drainage (INCID), December 9–11, 2009, Vigyan Bhawan, New Delhi, Paper available on website: http://cgwb.gov.in/documents/papers/INCID.html

Shekhar, S., Rao, S.V.N., 2010. Groundwater management in Palla well field of Delhi using numerical modeling technique – a case study. Bhu-Jal News 25 (3&4) and 26 (1&4) combined, 46–51, Paper available on website: http://cgwb.gov.in/documents/Bhujal%20Vol-25,2&3%20and%20Vol%2026,%201-4%20(Combined).pdf

Shekhar, S., Sarkar, A., 2013. Hydrogeological characterization and assessment of groundwater quality in shallow aquifers in vicinity of Najafgarh drain of NCT Delhi. J. Earth Syst. Sci. 122 (1), 43–54.

Singh, S.B., Mohiddin, S.K., Singh, P.N., Report 2005. Rainwater Harvesting Systems. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

Sinha, R., Kettanah, Y., Gibling, M.R., Tandon, S.K., Jain, M., Bhattacharjee, P.S., Dasgupta, A.S., Ghazanfari, P., 2009. Craton – derived alluvium as a major sediment source in the Himalayan Foreland Basin of India. GSA Bull. 121 (11/12), 1596–1610.

Soni, V., Shekhar, S., Singh, D., 2014. Environmental flow for the Yamuna river in Delhi as an example of monsoon rivers in India. Curr. Sci. 106 (4), 558–564.

Sprenger, C., (dissertation) 2011. Surface/groundwater interactions associated with river bank filtration in Delhi (India) – Investigation and modelling of hydraulic and hydro chemical processes. zur Erlangung des Doktorgrades des Fachbereichs, Geowissenschaften der Freien Universität, Berlin.

Vijay, R., Sargaonkar, A., Gupta, A., 2007. Hydrodynamic simulation of River Yamuna for riverbed assessment: a case study of Delhi Region. Environ. Monit. Assess. 130, 381–387.