

The controls on spatial and temporal variation of hydrochemical facies and major ion chemistry in groundwater of South West District, Delhi, India

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Abstract The existence of freshwater resource is a critical pre-requisite for any growing urban center. The South West District of Delhi is among the most rapidly developing urban areas of Delhi region. The freshwater requirement of this district is heavily dependent on groundwater due to absence of other sources. Groundwater availability as well as its quality is controlled primarily by geological features such as older alluvial in the western to central parts and quartzite exposure in the eastern part of the district. The groundwater flow direction and the presence of the Najafgarh drain in the district impact the groundwater quality as well as hydrochemical facies evolution. This article establishes spatial and temporal hydrochemical facies variation in groundwater of the district and its linkages with the geologic and anthropogenic factors.

Keywords Delhi · Quality · Groundwater · Hydrochemical facies · Anthropogenic control

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Introduction

The South West District of the National Capital Territory of Delhi covers a 420 km² area (CGWB 2006). The demographic details from the census of 2011 indicate that the population of 2.292 million in the district with density per km² of 5445 is highest in NCT Delhi (<http://www.censusindia.gov.in/pca/default.aspx>). This dense population leads to constraints on the groundwater resource, which is reflected in the fact that South West District experiences the highest annual groundwater draft among all the districts of NCT Delhi. Declining water levels at a rate of 1.2–2.4 m per year (Shekhar 2006) and overexploitation of groundwater (214 %) have further aggravated the problem (Chatterjee et al. 2009).

The groundwater in the South West District occurs in two types of formations, namely, Delhi quartzitic ridge that occurs in the eastern part of the district and fluvio-eolian deposits which covers the rest of the area (Fig. 1) (Shekhar et al. 2005). The alluvial parts of the district mainly comprise fluvial deposits alternating with eolian deposits, predominated by silt with medium to fine sand and clay sediments (Shekhar et al. 2005). The Najafgarh drain is a major surface water body in the area that divides the South-West District into the eastern and western parts (Fig. 1).

The hard rock areas covering about 18 km² (CGWB 2006) of the district is characterized by the fractures giving rise to secondary porosity (Bajpai 2011; Mukherjee et al. 2009). The confined aquifers in pediments, adjacent to the hard rock ridge, consist of silt, sand and gravel (Bajpai 2011) and have low groundwater potential of around 150–300 LPM (Shekhar et al. 2009, see Fig. 1). The groundwater occurs in confined conditions in the alluvial part and semi-confined to confined condition in the hard rocks.

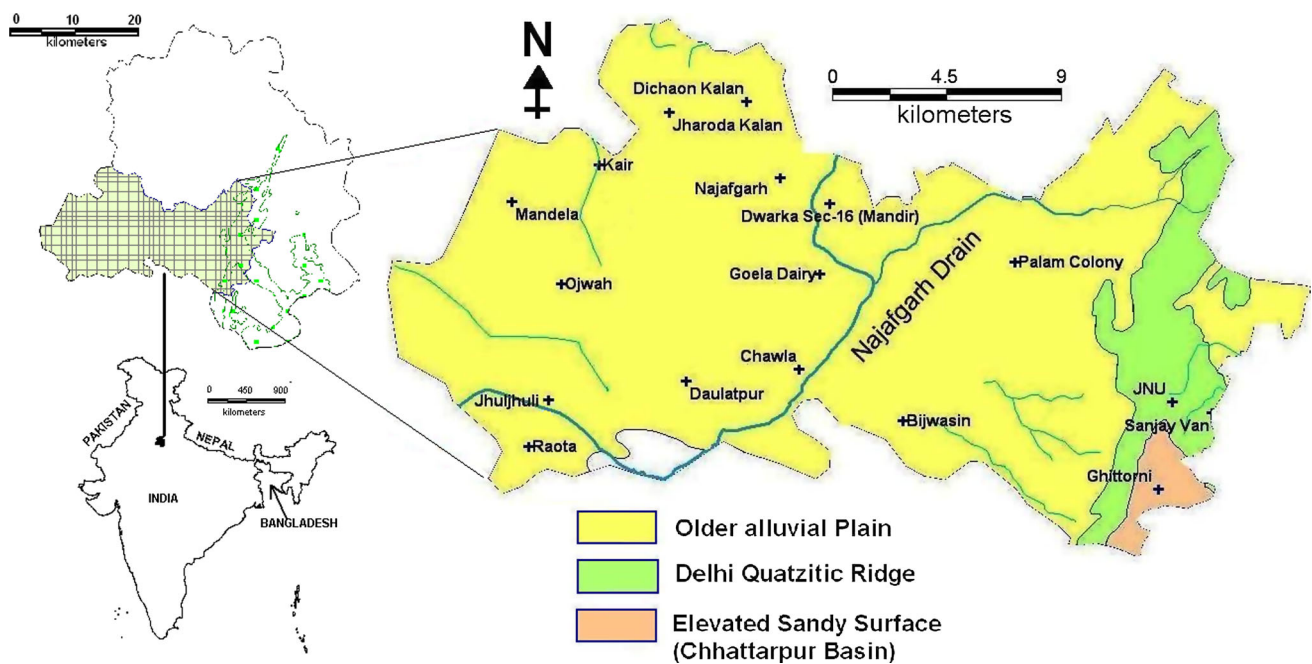


Fig. 1 Geological map of the South West District with sampling sites (modified from: Shekhar et al. 2005)

In recent years, rapid urbanization in the South West District has drastically changed land use pattern in the last decade. The development of a sub-city in the Dwarka area of the district (Fig. 1) and further expansion along highways have led to growth of moderately dense settlements in the eastern part of the district. (Kumar et al. 2013; Singh and Singh 2014). However, recent land use/land cover studies of NCT Delhi (Mohan et al. 2011; Kumar et al. 2013; Singh and Singh 2014) also reveal that the agricultural lands in the western part of the district have remained unaffected by this urbanization.

The change in the land use pattern of Delhi has resulted in greater stress on agriculture, leading to greater use of fertilizers and pesticides coupled with heavier abstraction in Delhi. Further, urbanization and industrialization in northern and eastern parts have led to heavier abstraction of groundwater.

Methodology

To ascertain the factors controlling the hydrochemical facies variation and major ion chemistry in the district, two sets of groundwater quality data from the years 2002 (Annexure 1a; Supplementary information) and 2010 (Annexure 1b; Supplementary information) were used. Only those sampling locations which were common for both the years were chosen for interpretation.

The hydrogeological conditions just before sampling were ascertained with the help of two maps prepared for

the district, namely: (1) a map showing the depth to water level and water table contour for pre-monsoon 2010 and (2) depth to fresh–saline interface in groundwater (after Shekhar et al. 2009). The first map was prepared using data from the Central Ground Water Board (CGWB) for May 2010, as it represented the groundwater dynamics of the study area at the time of sampling for groundwater quality. The surface elevation of groundwater monitoring stations were determined with the help of Google Earth data and verified with the surveyed elevation data available with CGWB and SRTM derived digital elevation model (DEM). The map was prepared by interpolating groundwater data and incorporated water level of the Najafgarh drain for the south-western part of the district, where the drain–groundwater system is connected.

The second map was based on studies conducted by Shekhar et al. (2009), in which variation in electrical conductivity with depth was set as the criterion to define the fresh–saline interface in groundwater. The standard electrical conductivity for fresh groundwater to define the interface was proposed to be $<1500 \mu\text{S}/\text{cm}$ (after Shekhar et al. 2005). The maps were prepared on Surfer and MapInfo softwares.

The historical groundwater quality data for the year 2002 (Shekhar 2004) was sampled by the second author and analyzed at the Central Ground Water Board (CGWB) chemical laboratory at Chandigarh, adopting the standard procedure set by BIS (1991). The groundwater quality data for the year 2010 was obtained from CGWB (2012). The groundwater samples were analyzed at the Central Ground

Water Board (CGWB) chemical laboratory at Chandigarh, using standard procedure set by BIS (1991).

The assessment of hydrochemical facies for the years 2002 and 2010 was done by preparing Piper plot using the AquaChem software (AquaChem 2007). The major ion chemistry and its temporal variation were also studied using various graphical plots.

Results

The depth to water level

The depth to water level (Fig. 2) in the district shows a gradual variation from west to east. The south-western part of the district comprising of localities such as Jhuljhuli, etc., have shallow depth to groundwater levels in the range of <5 m below ground level (mbgl). The deeper groundwater levels to the west of Najafgarh drain are observed toward the central part of the area near Kharkhari. It is also observed that while the depth to water level varies in the range of 20–25 mbgl in Kharkhari and Goela Dairy areas, in the zone surrounding this depression (Mandela, Daulatpur, Najafgarh, etc.), the depth to water level is in the range of 15–20 mbgl. In places close to the Najafgarh drain, the depth of water level ranges from 10 to 20 mbgl, except in south-western parts of the district near Raota (Fig. 2). This observation indicates that drain water and groundwater are only connected in the south-western part, while in other parts of the district the drain is disconnected from the groundwater system.

The depth to groundwater levels in the region to the east of the Najafgarh drain shows an increasing trend on moving from west to south-east toward the hard rock area and the direction of elevated ground (Fig. 2). As the

elevation gradually increases from west to south-east direction, the depth to water level also increases. In areas near Delhi ridge such as R.K. Puram and Rajokri, the depth to water level is >40 mbgl (Fig. 2). Ghittorni, located adjacent to Delhi ridge, has depth to water level of >50 mbgl.

Groundwater flow directions

An analysis of the water table contour brings out the basic groundwater flow direction in the district (Fig. 2).

The region west of the Najafgarh drain has a major depression in the water table around the Kharkhari area. On the east side of the drain, a similar depression is observed near Papankalan–Shekhwati lines (Fig. 2). These depressions, formed due to heavy groundwater extraction for irrigation around Kharkhari and domestic usage in Papankalan and Shekhwati lines, attract groundwater flows from surrounding areas and act as regional discharge areas. The elevated ridge in the eastern part of the district has a water table of >200 m above the mean sea level (MAMSL) and acts as the local recharge area (Fig. 2). The hydraulic gradient of regional depressions along with the higher water level elevation of the ridge controls the groundwater flow direction in the district. However, in the ridge area, uneven groundwater abstractions have produced a local depression in the water table (as in R.K. Puram; Fig. 2), which modifies the regional flow direction.

Fresh–saline water interface

The interface between fresh and saline water is defined as “a hydrostatic pressure surface in a dynamic equilibrium” which could be affected by several factors including fluctuation in the quantity of rainfall, surface flows, variation in

Fig. 2 The depth to water level and water table contour map of the South West District for pre-monsoon 2010

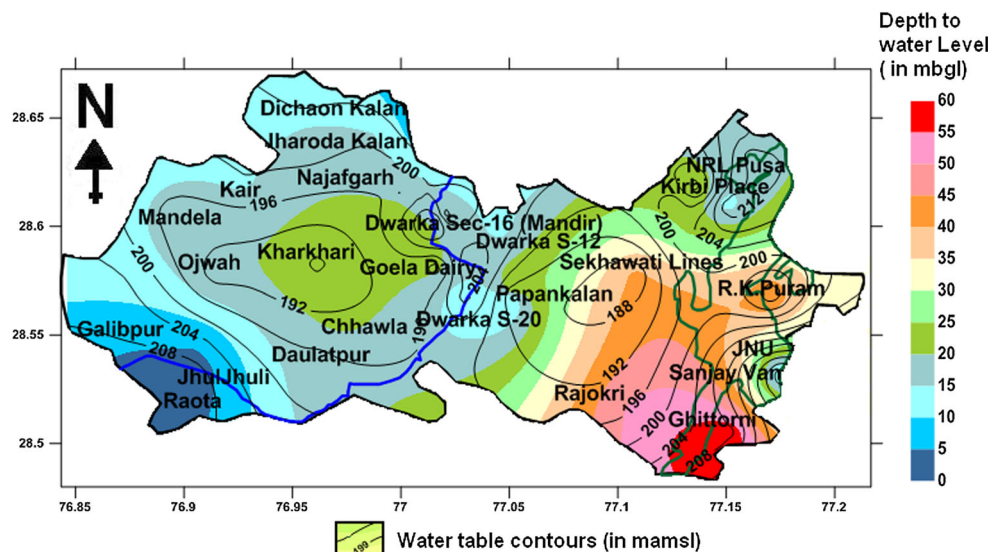
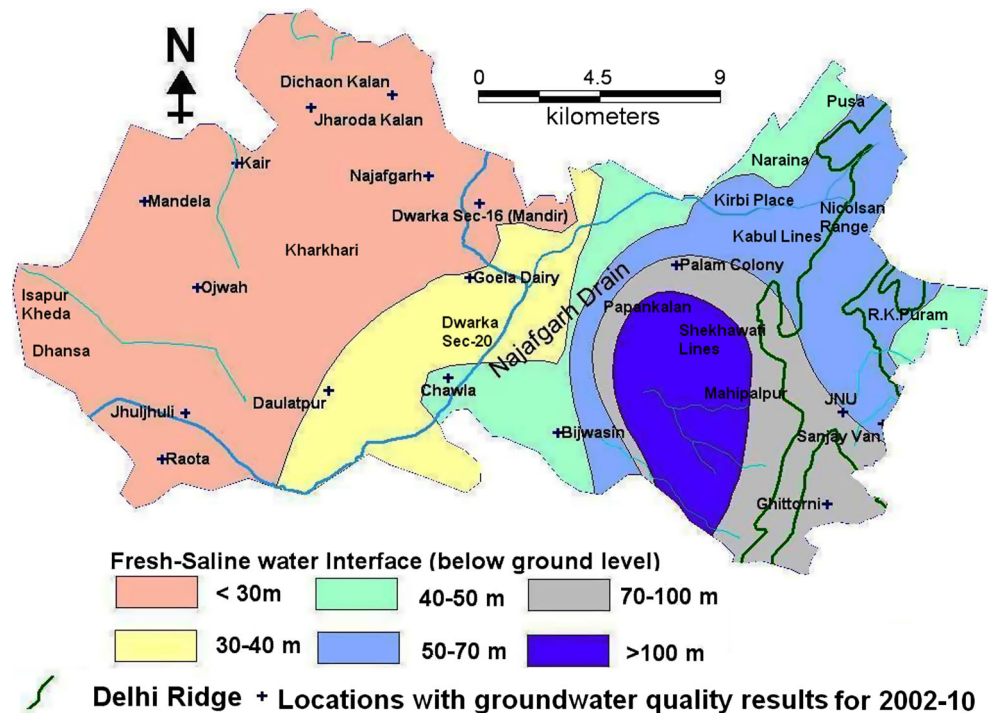


Fig. 3 Depth to fresh/saline water interface in South West District (source: Shekhar et al. 2009)



groundwater draft and nature of aquifer (Shekhar et al. 2005). The fresh–saline water interface in groundwater varies greatly in the entire area (Fig. 3). The areas west of Najafgarh drain and parts of Dwarka have a shallow freshwater layer up to 40 mbgl. The hard rock terrain in the eastern part of the district and areas adjacent to it has much deeper fresh–saline water interface in groundwater of around 80–90 mbgl (Shekhar et al. 2009). In major parts of the district, the depth to fresh–saline interface is in the range of <30 mbgl (Fig. 3).

Groundwater quality and hydrochemical facies variation

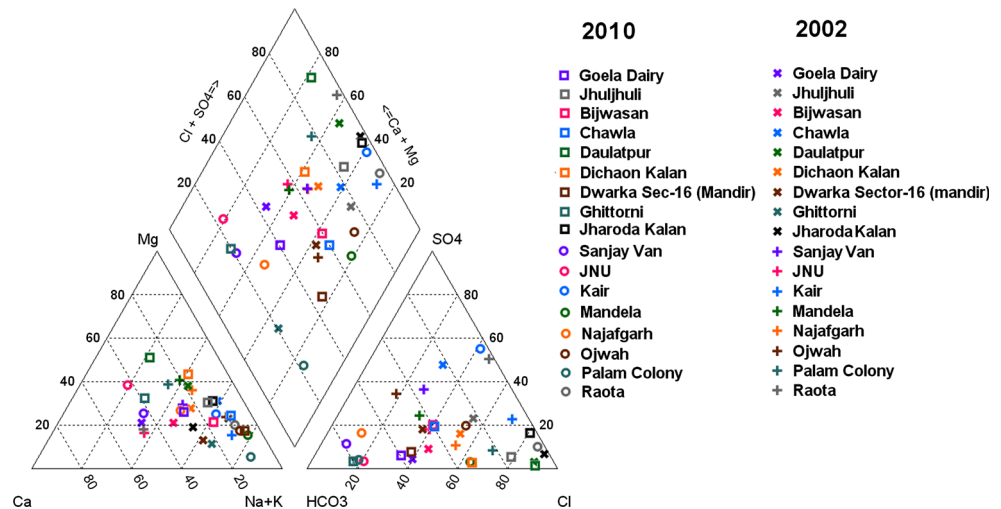
The varying fresh–saline water interface in groundwater is also responsible for high groundwater salinity in several areas of the district. Historical records show that even in 1970s and 1980s, the South West District was among the three saline groundwater pockets of Delhi (Subramaniam and Saxena 1983, CGWB 2006). Recent surveys have also pointed out that the highest electrical conductivity (EC) in Delhi region (16,700 $\mu\text{S}/\text{cm}$ at 25 °C) was recorded in Kair (Fig. 1), located in South West District (CGWB 2012). The salinity in groundwater in the Delhi region has been attributed to geogenic sources (Shekhar and Sarkar 2013; Shekhar et al. 2005; Lorenzen et al. 2012). Haque et al. (2013) emphasized the anthropogenic contamination of groundwater in Delhi along with an increase in the salinity.

The hydrochemical facies variation in the study area reveals a change in the general trend of the facies. The Piper plot for 2002 and 2010 (Fig. 4) shows that this trend varies from mixed type to chloride type of facies for the former and bicarbonate to chloride type of facies for the latter.

The Piper plot (Fig. 4) shows that in the year 2002, groundwater in some locations in hard rock and adjacent areas (Ghittorni, JNU and Sanjay Van) have bicarbonate to mixed type of hydrochemical facies, whereas many locations (Ojwah, Mandela, Dwarka sector-16, Chawla, Najafgarh, Dichaon Kalan Bijwasan and Goela Dairy) in older alluvium areas show mostly mixed-type facies ($\text{Ca-Na-SO}_4\text{-Cl}$, $\text{Na-Mg-SO}_4\text{-Cl-HCO}_3$, Na-Mg-Cl-HCO_3) (Figs. 1, 4). The presence of sodium chloride, i.e., Na-Cl-type facies has also been observed in some locations in the older alluvial plains such as Palam colony, Jhuljhuli, Raota, Kair, Jharoda Kalan and Daulatpur (Figs. 1, 4).

The Piper plot (Fig. 4) shows that for the year 2010, the groundwater in the Delhi ridge, adjacent areas and near water bodies (Ghittorni, Sanjay Van, JNU, Palam colony, Najafgarh, Dwarka sector 16 and Goela Dairy) are predominantly of bicarbonate type, i.e., Ca-Na-HCO_3 , $\text{Ca-Mg-HCO}_3\text{-SO}_4$ or Na-Ca-Cl-HCO_3 (Figs. 1, 4). While groundwater from many older alluvial areas (Jhuljhuli, Raota, Kair, Daulatpur and Jharoda Kalan) shows more Na-Cl-type facies in comparison to mixed-type facies observed in year 2002.

Fig. 4 Hydrochemical facies variation in South West District in 2002 and 2010



On the basis of geomorphology, the hydrochemical facies evolution from 2002 to 2010 could be broadly grouped into four categories:

- (a) Areas in hard rock terrain and its adjacent elevated sandy areas (Chattarpur basin) such as Ghittorni, JNU and Sanjay Van, earlier identified as recharge zone, show persistence of bicarbonate facies over the period.
- (b) The area adjacent the above-mentioned recharge zone such as Palam colony and Bijwasan show evolution of facies from mixed type to bicarbonate type.
- (c) Areas in older alluvial plains close to Najafgarh drain such as Najafgarh, Dwarka sector 16 and Goela Dairy have retained mixed facies characteristics. However, over the years, the dominance of bicarbonate has increased.
- (d) Areas in older alluvial plain far away from the Najafgarh drain, such as Ojwah, Jhuljhuli, Raota, Kair, Daulatpur and Jharoda Kalan, have persistent chloride-type facies, with enrichment in chloride ions over the years.

Comparing of facies for years 2002 and 2010 in the Piper plot (Fig. 4) reveals the geological and anthropogenic controls on hydrochemical facies evolution in different locations of the district. The difference in symmetry in the diamond plot for the years 2002 and 2010 (Fig. 4) is an indicator of this. A further insight into the hydrochemical facies variation was done by incorporating depth to water level and depth to fresh–saline interface in groundwater as a variable.

Hence, we selected three representative locations to further establish controls to hydrochemical facies variation in the district:

1. Ojwah from older alluvial plains (Fig. 1) with shallow depth to fresh–saline interface (Fig. 3) and intermediate depth to water level in the range of 15–20 mbgl (Fig. 2).
2. Najafgarh from the older alluvial plains near the Najafgarh drain (Fig. 1) with intermediate depth to fresh–saline interface in the range of 30–40 mbgl (Fig. 3) and intermediate depth to water level in the range of 15–20 mbgl (Fig. 2).
3. Ghittorni from adjacent to Delhi ridge (Fig. 1) with deep fresh–saline interface in the range of 70–100mbgl (Fig. 3) and depth to water level >55 mbgl (Fig. 2).

These three locations show distinct facies variation from 2002 to 2010 (Fig. 4). Ojwah reveals a change of hydrochemical facies from Na–Mg–HCO₃–SO₄ type to Na–Cl–HCO₃ type of facies. Groundwater in Ghittorni showed no significant change in anionic concentrations, but enrichment in calcium concentrations over the period of 8 years was reflected in hydrochemical facies variation (Na–Ca–HCO₃ type to Ca–Mg–Na–HCO₃ type). In the Najafgarh area, the hydrochemical facies had re-evolved from Na–Mg–Cl–HCO₃ type to Na–Ca–Mg–HCO₃ type.

The changes in hydrochemical facies are also reflected in the temporal changes in the overall groundwater quality.

A semi-logarithmic scatter plot based on the Wilcox/conductivity versus SAR (C–S) diagram (Fig. 5) reveals that the general electrical conductivity of the groundwater has increased over the period of 8 years with around 60 % of the samples showing increased sodium level. This change is more prominent in groundwaters from older alluvium (Fig. 1). As observed from the two polygons on the plot, the C–S footprint for the majority of the samples show enrichment in sodium absorption ratio (SAR) values over the period of 8 years.

Fig. 5 Scatter plot for SAR vs electrical conductivity for 2002 and 2010. The two polygons on the plot encompass grouping of 2002 and 2010 data

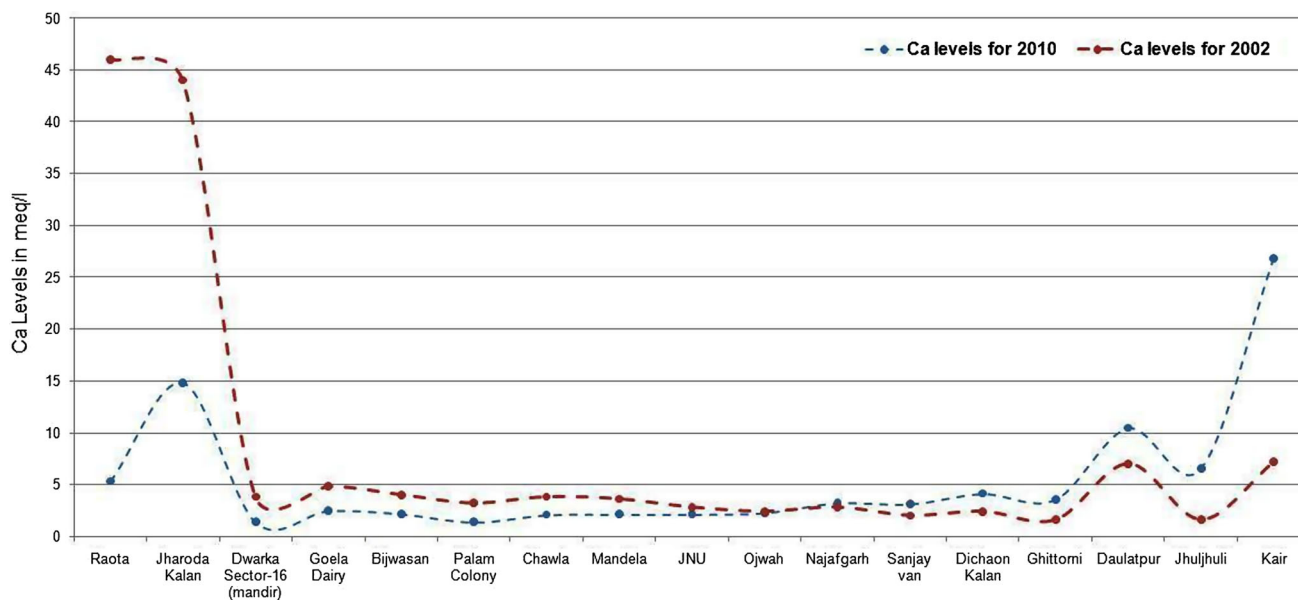
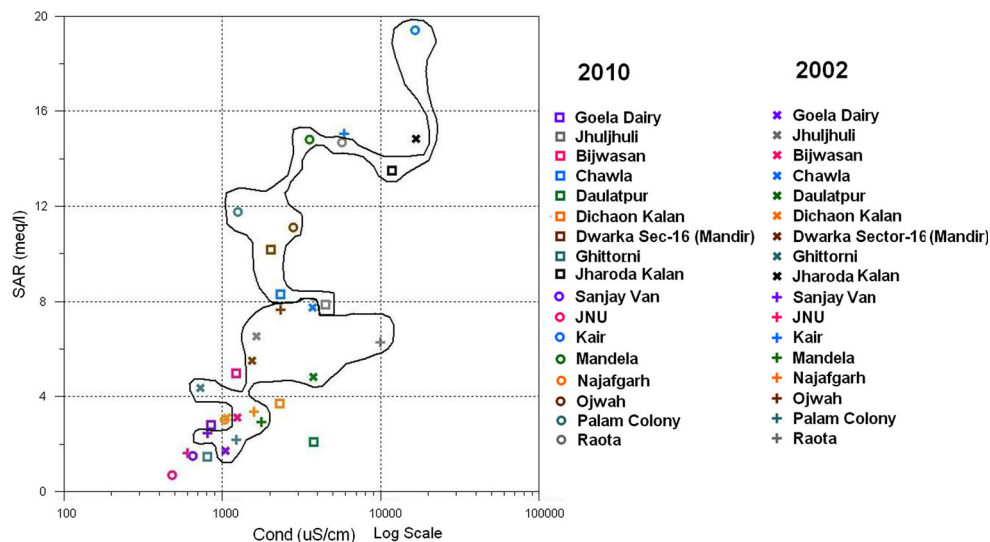


Fig. 6 Temporal variation in calcium concentration in the study area

Similarly, changes in the calcium concentration in groundwater over the period of 8 years are also observed (Fig. 6).

The temporal variation in calcium concentration in groundwater results in three distinct categories:

1. decline in calcium concentration in groundwater as observed in Raota, Jharoda Kalan, Dwarka sector-16 (mandir), Goela Dairy, Bijwasan, Palam Colony, Chawla and Mandela (Fig. 1);
2. no significant change in calcium levels as observed in JNU, Sanjay Van, Ojwah and Najafgarh (Fig. 1);
3. calcium enrichment in groundwater as observed in Kair, Jhuljhuli Ghittorni, Daulatpur and Dichaon Kalan (Fig. 1).

The depletion of calcium ions in groundwater has been observed in older alluvial areas. The older alluvium of Delhi has mostly fine sediments with dominance of clay admixed with silt and calcareous concretions (Shekhar and Prasad 2009). These calcareous concretions are reported to be fairly hard compact nodular masses (Sett 1964). A similar nature of sediments with prominence of ‘caliche’ nodules has also been observed in older alluvial Gangetic plains in

Bihar (Saha et al. 2008, 2010) with dominance of sodium ions over calcium ions in groundwater. This was attributed to the ion-exchange process explained by the equation:



(Saha et al. 2008)

We propose that a similar ion-exchange process leads to formation of calcareous concretions and release of sodium ions in groundwater of the older alluvium in the study area. Datta and Tyagi (1996) also emphasized the possibility of precipitation of calcium as calcium carbonate in aquifers of Delhi. Singh et al. (2015) suggested that dissolved CO₂ in subsurface water encouraged silicate weathering, which released sodium in the groundwater system.

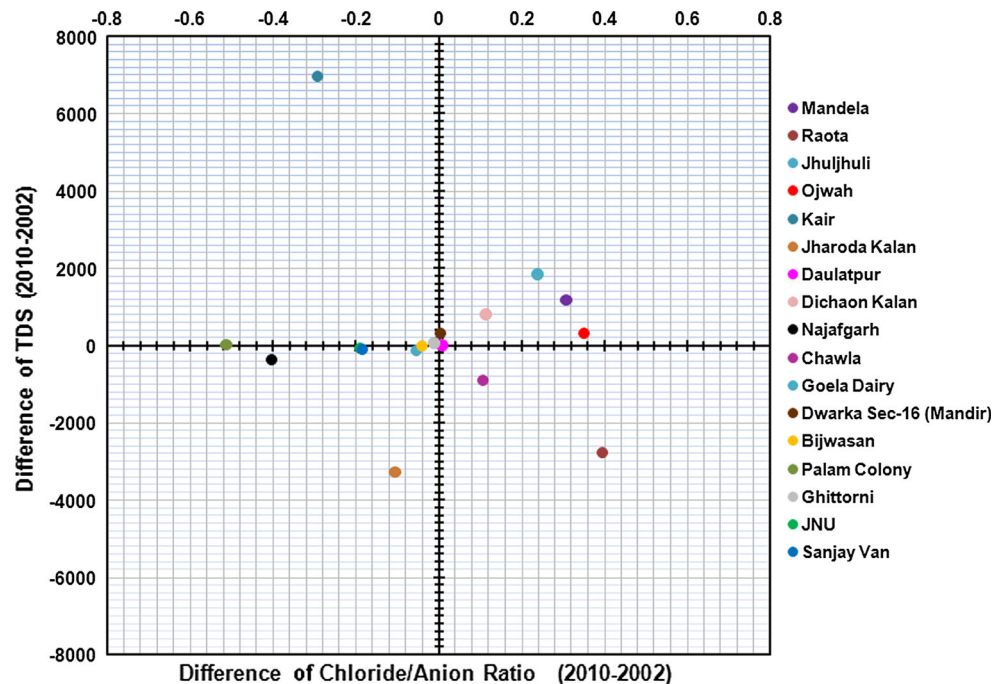
The calcium enrichment in groundwater is possibly guided by two different processes. In places located in older alluvial plains such as Dichaon Kalan and Daulatpur, it is possible that decline in water levels over the period of 8 years exposed the calcium-rich calcareous concretions that were oxidized to release calcium ions in groundwater. While in Ghittorni, located adjacent to the hard rock terrain, recharge of groundwater in undisturbed aquifer led to evolution of Ca–HCO₃ type of facies. Datta and Tyagi (1996) also emphasized that local recharge in Delhi was associated with low salinity of water of the Ca–Mg–HCO₃ type.

The temporal variation of chloride with respect to changes in total dissolved solids (TDS) over the period of 8 years is represented by a time–difference T–Cl plot (Fig. 7), where T–Cl stand for TDS and Cl. The plot represents difference of the Cl/total anions ratio over a given

time versus difference in TDS over the same time period. The plot shows different scenarios of chloride variation:

- (a) The first scenario is observed in locations in older alluvial plains such as Ojwah, Dichaon Kalan, Jhuljhuli and Mandela with enrichment of chloride along with increase in TDS over the time. All these location also show increase in sodium levels over a period of 8 years (Fig. 5).
- (b) The second scenario is observed in Dwarka sector-16 (mandir), Ghittorni and Daulatpur with no significant change in chloride and TDS over the period of 8 years.
- (c) The third scenario is observed in Palam Colony, Najafgarh, Sanjay Van, JNU, Goela Dairy and Bijwasan with decrease in chloride, but no significant change in TDS over the time.
- (d) The fourth scenario is observed in Chawla and Raota with enrichment of chloride and decline in TDS. Both these locations have shown evolution of hydrochemical facies from sulfate (SO₄) dominance to chloride (Cl) dominance and decline in calcium concentration over the period of 8 years (Figs. 4, 6).
- (e) The fifth scenario represents drastic increase in TDS and decline in chloride as observed in Kair. This particular location has shown drastic increase in calcium (Fig. 6) and facies changes from Cl type to Cl–SO₄ type over the period of 8 years (Fig. 4).
- (f) The sixth scenario shows a decline in chloride and TDS over a period of 8 years in Jharoda Kalan.

Fig. 7 Time difference T–Cl plot for 2002–2010



Though both calcium (Fig. 6) and SAR (Fig. 5) have declined, the anionic facies (Na–Ca–Cl type to Na–Mg–Cl type of facies) showed no significant changes (Fig. 4). This clearly indicates freshening of older saline groundwater.

Discussions

It is proposed that both geogenic and anthropogenic factors are responsible for major ion chemistry and hydrochemical facies variation in the district. Geology of the area is primary control on the groundwater quality variation (Sett 1964; Datta and Tyagi 1996), however the anthropogenic imprints are visible. It is observed that over a period of 8 years, the hydrochemical facies of groundwater from localities like JNU Campus and Sanjay van on Delhi ridge (Fig. 1) have re-evolved from bicarbonate dominant mixed facies to distinctly bicarbonate type of facies (Fig. 4). The decline in sodium and chloride levels (Figs. 5, 7) with no significant change in TDS and calcium levels (Figs. 6, 7) for these places also indicate dilution by freshwater. This dilution is on account of the fact that over the years, JNU has emerged as the local recharge area in the hard rock terrain (Fig. 2). This is partly due to the creation of four check dams with 49048 m³ of total reservoir capacity in JNU and Sanjay Van areas (CGWB 2008) in the late 1990s. An increase in water levels in JNU up to 2.55 m during the post-monsoon season observed by Chatterjee et al. (2009) has been accounted for by recharge through these check dams. Thus, continuous flushing of groundwater coupled with addition of fresh meteoric water at enhanced rate by recharge through check dams in JNU gives rise to changes in the major ion chemistry over a period of 8 years.

In the closely adjacent area (Ghittorni; Fig. 1), there has been no significant change in TDS and chloride (Fig. 7), and decline in SAR (Fig. 5) and enrichment of calcium have been observed (Fig. 6). This is on account of the fact that the site (Ghittorni; Fig. 1) has open scrub, with artificial recharge projects implemented by the local agency (as observed during field survey) and it is also a recharge area (Fig. 2).

The rock–water interaction due to dissolution or chemical weathering of aquifer material is usually observed as a major geogenic factor for change in groundwater quality in alluvial plains all over the globe (Varol and Davraz 2014; Ben Alaya et al. 2014; Reddy 2013; Singh et al. 2015). In this perspective, in South West District also, ion-exchange process is a dominant phenomenon.

In older alluvial plains, the facies footprint shows hydrochemical facies evolution over a period of 8 years from predominantly mixed facies occurring along with chloride

facies to predominantly chloride facies along with mixed facies (Figs. 1, 4). The older alluvial areas of the district have relatively shallow depth to water level (Fig. 2) and shallow depth to fresh/saline interface in groundwater (Fig. 3). On account of increased groundwater abstraction, regional depressions in the water table elevation have been seen near the Kharkhari and Papankalan–Shekhawati lines areas (Fig. 2). These depressions, along with upconing of saline groundwater, led to shifting of hydrochemical facies toward chloride dominance. However, Kair and Jharoda Kalan showed that chloride-type facies and salinity in groundwater were not always linked to enrichment of chloride in groundwater (Fig. 7).

The recharge from the prominent water body (Najafgarh drain), which is unlined in South West District (Shekhar and Sarkar 2013) also has significant control on major ion chemistry and hydrochemical facies evolution in the district. The water quality in Najafgarh drain is relatively better for the stretch of the drain flowing across the South West District (Shekhar and Sarkar 2013). However, the impact of this recharge is varied. In areas showing relatively deeper water level with declining trend such as Najafgarh and surrounding areas (Fig. 2), the freshening is on account of seepage from the drain. This leads to re-evolution from mixed (HCO₃–Cl)-type facies to bicarbonate-type facies with no significant change in TDS (Fig. 7). A similar observation was made by Shekhar and Sarkar (2013) on facies change near Najafgarh drain of the district. In shallow water level areas such as Raota, Chawla, Jhuljhuli and adjacent areas (Fig. 2), the recharge by drain seepage in waterlogged areas causes chloride enrichment in groundwater (Figs. 4, 7). The profound use of fertilizers in agricultural activities in these sites further contributes to groundwater contamination (Datta et al. 1997). The recharge in nearby shallow aquifers from Najafgarh drain, which was reported by Shekhar and Sarkar (2013), is often triggered by continuous high groundwater abstraction. Hence, high groundwater abstraction is an important anthropogenic factor which controls the hydrochemical facies changes.

Conclusions

The article identifies various controls on evolution of hydrochemical facies and changes in major ion chemistry in the study area. Though primary control on major ion chemistry and hydrochemical facies is geologic, anthropogenic factors have left their distinct footprint on groundwater quality evolution. The changes in land use in the last few years has affected groundwater abstraction pattern in the district, particularly in older alluvial parts of the district. The excessive groundwater abstraction has

triggered upconing of saline groundwater in different parts of the older alluvial plains and induced recharge from the Najafgarh drain in shallow aquifers close to it. This induced recharge has led to dilution of groundwater in older alluvium near the drain, while in hard rock terrain artificial recharge leads to dilution of groundwater. Hence, it can be interpreted that both groundwater abstraction and artificial recharging are the two fundamental anthropogenic controls on the groundwater dynamics and hydrochemical facies variation in the district over the years. The hydrochemical facies evolution is triggered mostly by these anthropogenic factors. Further, the proper understanding of these factors could assist in wastewater management and regulated groundwater abstraction for mitigation of the long-lasting issues related to the groundwater quality in the area.

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