


Hydrogeochemical and isotopic insights into mineralization processes and groundwater recharge from an intermittent monsoon channel to an overexploited aquifer in eastern Haryana (India)

P. Baudron^{1,2,3}  · C. Sprenger^{4,5} · G. Lorenzen⁵ · M. Ronghang⁶

Received: 5 February 2015 / Accepted: 8 August 2015 / Published online: 24 February 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract This study aimed at characterizing the groundwater flow pattern in a semi-arid agricultural area in northern India crossed by an intermittent monsoon-controlled watercourse, the Najafgarh drain. More specifically, it focused on studying the impact of groundwater recharge from the riverbed to the regional aquifer using hydrogeochemical and isotopic data. Significant hydrogeochemical zonation was observed between the northern, central and southern sides of the drain, linked to different mineralization processes and mixings. Northward from the drain, groundwater was mainly brackish (4.1–23.4 mS/cm), due to dissolution of evaporites (halite and anhydrite). Southward from the drain, mostly fresh groundwater was found (from 0.5 to 2.3 mS/cm), revealing notable cation exchange processes. In the vicinity of the drain (central area), mineralization was intermediate (0.7–4 mS/cm) and groundwater showed low geochemical evolution, supposing a distinct origin. Stable isotopes of water ($\delta^{18}\text{O}$, $\delta^2\text{H}$) confirmed that central groundwater was not a simple

mixing between northern and southern groundwater masses, but had a significant component of infiltrated surface water from the drain. Potentiometric data supported these findings and confirmed the contribution of the drain to the recharge of the aquifer, setting up a hydraulic barrier between north and south, despite surface water availability limited to the monsoon season and low hydraulic conductivity of the riverbed. This study demonstrates the value of the geochemical and isotopic analysis of groundwater to characterize groundwater flow pattern in peri-urban agricultural areas, especially surface water–groundwater interactions.

Keywords Groundwater recharge · Overexploitation · Hydrochemistry · Stable isotopes of water · Najafgarh drain · India

Introduction

Population growth and the development of irrigation-based agriculture, together with uneven distribution of seasonal rainfall, have put severe pressure on water resources, leading in many places worldwide to the overexploitation of groundwater (e.g., Custodio 2002; Massuel et al. 2013; Baudron et al. 2013, 2014). In India, this resource is of critical importance (Massuel et al. 2009; Lorenzen et al. 2010; Perrin et al. 2011; Brindha and Kavitha 2014; Katpatal et al. 2014; Murkute 2014; Dwivedi et al. 2015). In the southwestern district of the Indian capital Delhi and its neighboring state Haryana, water supply management faces two major problems: limited groundwater resources affected by salinity ingress and erratic availability of surface water.

The Najafgarh drain (Fig. 1), an intermittent water channel flowing eastward until reaching the Yamuna River in Delhi, is not integrated as a water source because of the

✉ P. Baudron
paul.baudron@polymtl.ca

¹ Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, C.P. 6079 Succ. Centre-Ville, Montréal, QC H3C 3A7, Canada

² IRD, UMR G-EAU, BP 5095, 34196 Montpellier Cedex 5, France

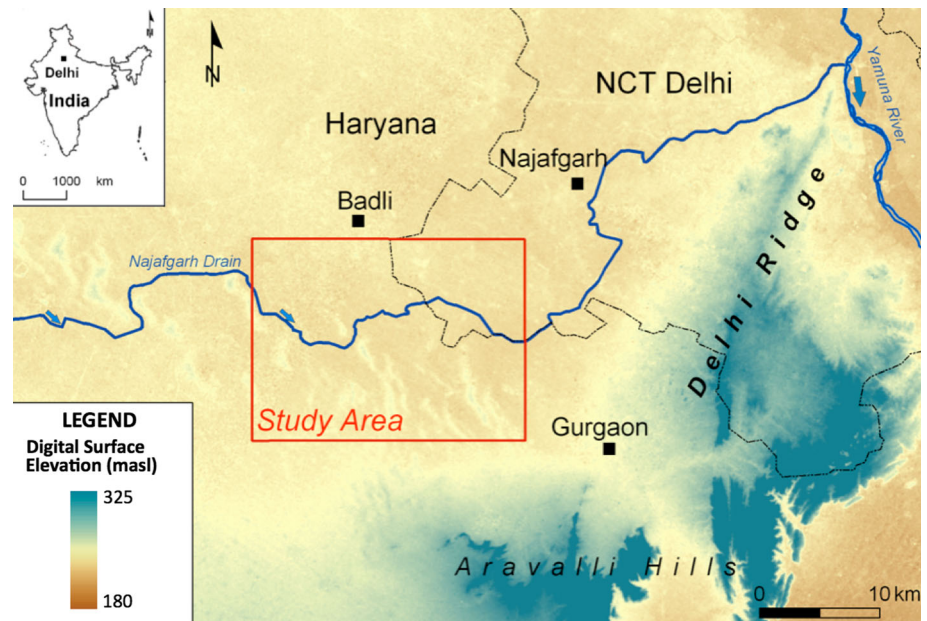
³ GEOTOP Research Center, Montréal, Canada

⁴ Kompetenzzentrum Wasser Berlin, Cicerostr. 24, 10709 Berlin, Germany

⁵ Freie Universitaet Berlin, Malteserstr. 74-100, 12249 Berlin, Germany

⁶ Department of Civil Engineering, Bineswar Brahma Engineering College, Kokrajhar, BTAD, Assam 783370, India

Fig. 1 Overview of ground surface elevation with main hydrological and geomorphological features of the study area



uneven annual distribution of water, linked to the monsoon. In the end, the fresh water it carries during the annual monsoon discharge flows towards the city of Delhi where it is polluted by raw sewage. Why not make this discharge usable before it is polluted? Well injection techniques (e.g., aquifer storage and recovery) or in-channel modifications (e.g., check dams) could be promising ways to enhance recharge for groundwater replenishment and quality improvement.

However, no specific infrastructure was available for long-term surface and groundwater sampling and monitoring, and the intermittent regime of the Najafgarh drain appeared to be a serious limitation for a consistent recharge from the drain to the aquifer. In addition, the riverbed and the banks were shown to have a limited hydraulic conductivity, which restricts the infiltration potential (Baudron 2008). Therefore, to understand the dynamics of groundwater flow in the area and assess whether the drain has a significant impact on recharge, it was decided to perform a study of the regional hydrogeochemistry, with a special focus on mineralization and mixing processes. To this end, 19 tubewells and hand pumps were sampled.

Study area

Geomorphology and climate

The study area is a plain terrain, with an average elevation of 213 meters above sea level (m asl). The Najafgarh drain flows from west to east across the central part of the study area. A long continuous chain of rocky ridges, locally called Delhi Ridge, rises up to 320 m asl, 20 km

southeastward of the study area (Fig. 1). The climate is of semi-arid nature; 80 % of annual rainfall occurs during monsoon (July–September). Annual precipitation is between 720 mm (Delhi), 510 mm (Badli) and 400 mm (Najafgarh) (CGWB 2006). In Delhi, the seasonal average temperature varies from 18.7 to 30.5 °C (Kumar et al. 2006).

Najafgarh drain

The Najafgarh drain was dug at the beginning of the nineteenth century along an old course of the Sahibi River, an intermittent river emanating from more than 150 km southwest, in the State of Rajasthan (Mohan 2007). It is connected to several other drains and rivers that belong to the Northern Indian Storm Water and Irrigation canal Network. It is interrupted by a weir at the interstate border between Haryana and Delhi. Although the upper segment in Haryana State (study area) falls dry in summer (Fig. 2), it receives surface runoff and storm water from the Sahibi catchment in the Aravalli range during monsoon (AGC 2001). Downstream in Delhi, it was canalized to drain a morphological depression in western Delhi (Najafgarh Jheel) and integrated into the storm water and sewer drainage system of the city (Nema and Agarwal 2003). The discharge of the Najafgarh drain is controlled by monsoon (Flood Control Wing 1976).

Geology and aquifer characteristics

The study area is located in the Ganga Plain within the world's largest terrestrial foreland basin, the Himalayan



Fig. 2 View of the Najafgarh drain before and after a strong rain event in April 2008

Table 1 Lithostratigraphic units (modified from Thussu 2006)

Age	Group/formation	Lithology
Quaternary		
Holocene	Younger alluvium	Grey, fine to medium sand, grit with coarse sand, silt and clay
	Aeolian deposits	Yellowish brown medium sand with silt, calcrete (kankar)
Pleistocene	Older alluvium	Polycyclic sequence of sand–silt–clay with bedded or nodular calcrete (kankar)
Proterozoic	Alwar group	Quartzite with thin bands of mica-schist

molasse basin. The main lithostratigraphic units are described below and summarized in Table 1. The Delhi Ridge, from the Alwar group, is the only outcrop of the bedrock, composed of Precambrian quartzitic rocks with thin bands of mica-schist. Overlying the Delhi Ridge and reaching thicknesses up to 300 m (Shekhar and Sarkar 2013), the Quaternary formation is composed of Pleistocene to Holocene medium to fine-grained sand with varying content of silt and clay, together with local aeolian deposits (see Table 1). It forms fairly thick aquifers, generally semi-confined. The presence of calcrete nodules

(also called “kankar”) in these sediments is a classical feature of the Ganga Plain. Little information on the hydrodynamic properties of the Quaternary formation is available. Nonetheless, Shekhar and Sarkar (2013) mentioned, at some locations, hydraulic conductivity below and adjacent to the Najafgarh drain ranging from 3 to 28 m/day and transmissivity ranging from 63 to 928 m²/day.

Methods

A hydrogeological survey was carried out to obtain an overview of the main mineralization and mixing processes in the area as potential indicators of geochemical areas and groundwater flow patterns. In April 2008, 19 groundwater samples (hand pumps and tubewells) were collected and in situ parameters (pH, T, EC, DO) were measured with Eutech devices. Alkalinity was determined by HCl titration in the field using a Merck field kit. All water samples were stored in 20 ml polypropylene (PP) bottles. All samples for ion determination were filtered on site with 0.2 mm acetate cellulose filters. The sample for cation measurements was acidified to pH 2 with pure HNO₃ and one bottle of each sample (not acidified) was kept for anion determination. Additionally, one 20-ml PP bottle was taken for stable isotopes of

water ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) measurement. Isotope analysis was performed at the Freie Universitaet Berlin on a Thermo Finnegan Mat 253 isotope ratio spectrometer using a Gas Bench II peripheral unit with autosampler-assisted loop injection.

For $\delta^{18}\text{O}$ and $\delta^2\text{H}$ measurements, a sample volume of 1000 μl was flushed with 0.5 % CO_2 in helium (He) environment and then equipped with platinum catalyst to accelerate equilibrium. Measurement was performed after an equilibration time of 40 min. Precision was ± 0.6 (‰ VSMOW) for $\delta^2\text{H}$ and ± 0.02 for $\delta^{18}\text{O}$ (‰ VSMOW). Analytical values were standardized to the international reference, Vienna Standard Mean Ocean Water (VSMOW). Water samples were analyzed for K, Na, Ca and Mg by the ICP Optima 2100 Perkin Elmer with a detection limit of 0.02 mg/l and for Br, Cl, SO_4 by ICS 1100 with a detection limit of 0.1 mg/l. A reliability check based on electrical balance was made and only samples with ion balance (IBE) ≤ 10 %, calculated from Eq. 1 were used for further interpretation:

$$\text{IBE} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100. \quad (1)$$

Table 2 presents the hydrochemistry, ion balance error and several saturation indexes. Whenever possible, water table elevation was measured manually with a dip meter. Although at certain places it was possible to dismantle hand pumps and measure the depth to water table from the borehole directly, some measurements were made in abandoned dug wells. Due to the declining groundwater table, many of the dry dug wells are equipped with suction pumps standing on the bottom of the dug well, a few meters below ground level. Under normal atmospheric pressure, suction pumps can draw water up to a maximum height of approximately 10 m. This basic principle makes it possible to estimate the depth to water table at dug wells equipped with suction pumps to be a maximum 10 m below the bottom of the dry dug well. Figure 3 illustrates estimated depth to water table as dotted circles. At each of the sampling points, ground level elevation was measured by a Garmin Legend-C GPS, and checked by topographical maps and a digital surface model (Fig. 1) was derived from SRTM data.

Results

Water table elevation

Figure 3 shows the elevation of groundwater table and ground surface in m asl, derived from SRTM data and from the GPS measurements of water level. Given the limited number of water table measurements, only local

equipotential lines were drawn. Two trends appear in Fig. 3: (1) the Delhi Ridge (and Aravalli Hills), rising up 20 km southwards from the drain, is the most important source of groundwater recharge for the area, as water table levels are higher in the south than in the north, an observation also confirmed by Kumar et al. (2011) and (2) water table is higher along the drain than in the northern and the southern areas, suggesting a flow from the drain to the north, and from the drain to the south.

Although no data are available about the decrease of the groundwater level in the area over the last decades, field observations and information from locals clearly indicate the depleted groundwater state, as well as the progressive salinization of the groundwater. Overexploitation of the alluvial aquifer, mainly for irrigation purposes, seems to be the main cause.

Hydrogeochemistry

Groundwater presents a large variability of hydrogeochemical water types: Ca- HCO_3 , Na- HCO_3 , Ca-Cl, Mg- HCO_3 , Mg-Cl and Na-Cl. Electrical conductivity (EC) varies from 0.5 to 23.4 mS/cm (Table 2). Based on these geochemical characteristics, groundwater samples can be divided in three major groups, as shown in the Piper diagram (Fig. 4). It is important to note that these geochemical signatures correspond to specific geographic areas, as illustrated by the Stiff diagrams represented on the map of the area (Fig. 5). Indeed, the first area (“south”) corresponds primarily to samples taken southward from the drain where groundwater is partly fed from the Ridge, in accordance to the regional groundwater flow pattern. The water from the corresponding five samples was found to be mainly Ca- HCO_3 and Na- HCO_3 type, with EC between 0.5 and 2.3 mS/cm. The second area (“center”) corresponds to groundwater sampled close to the drain (except no. 17). It contains seven samples, mostly with HCO_3 -Cl to Na-Cl water types and EC values between 0.7 and 4 mS/cm. The third area (“north”) corresponds to groundwater samples taken northward from the drain. It consists of seven waters of Mg-Cl and NaCl water types with high salinities (EC from 4.1 to 23.4 mS/cm).

Stable isotopes of water

All samples plot below the Global Meteoric Water Line (GMWL) and, except for one, below the Local Meteoric Water Line (LMWL) for New Delhi (Datta et al. 1991) (Fig. 6). The most enriched signatures ($\delta^{18}\text{O}$ mostly between -5.5 and -4 ‰ VSMOW) include all samples from the north and south areas. The most depleted signatures correspond to the central area and are aligned

Table 2 Sampling ID, sampling date, location, physicochemical in situ parameter, hydrochemistry and stable isotope results

ID	Type	Group	Lat.	Long.	Sampling date	EC (μS/cm)	Temp. (°C)	pH	HCO ₃ (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)
1	TW	Center	76.80	28.51	04/03/08	2900	27.4	7.2	378	153	62	284	8
2	HP		76.79	28.51	27/03/08	1366	24.6	7.4	482	78	91	232	1.7
3	HP		76.74	28.51	04/04/08	1703	–	–	317	67	55	253	5.7
4	HP		76.80	28.53	11/04/08	3950	32.0	6.9	775	100	156	683	9.8
5	TW		76.91	28.47	27/03/08	1190	26.8	7.5	329	66	55	151	5.4
6	HP		76.87	28.54	27/03/08	1414	27.0	7.2	512	59	55	224	2
7	TW		76.82	28.50	25/03/08	728	27.3	7.5	305	69	43	54	2.8
8	HP	South	76.84	28.49	03/04/08	984	24.8	7.0	702	62	43	148	3.8
9	TW		76.75	28.53	30/03/08	454	27.8	7.6	488	32	52	147	11.8
10	FW		76.75	28.52	10/04/08	2340	27.0	7.2	506	78	67	429	2.9
11	HP		76.87	28.46	27/03/08	1380	27.8	7.7	573	33	35	310	1.8
12	TW		76.89	28.47	30/03/08	1700	26.5	7.4	659	26	44	315	8.5
13	TW	North	76.84	28.55	25/03/08	6600	27.3	7.3	403	168	356	1230	16
14	TW		76.78	28.55	04/04/08	23,400	27.3	6.8	232	893	1335	5430	21.5
15	TW		76.76	28.53	04/04/08	6880	26.8	7.2	348	394	374	763	403
16	FW		76.83	28.54	02/04/08	5200	26.3	6.9	354	341	227	687	6.6
17	TW		76.79	28.51	30/03/08	7800	26.8	7.1	378	262	392	1217	11.8
18	TW		76.87	28.54	29/03/08	4820	28.1	6.8	415	182	220	786	5.4
19	TW		76.87	28.53	04/04/08	4110	23.0	6.9	336	196	164	358	4.2

ID	Cl (mg/l)	SO ₄ (mg/l)	NO ₃ (mg/l)	Br (mg/l)	Cl/Br (weight)	δ ¹⁸ O ^a	δ ¹⁸ O err. ^a	δ ² H ^a	δ ² H err. ^a	IBE (%)	SI Calc.	SI Dolo.	SI Anhy.
1	524	183	2	1.6	327	−7.1	0.05	−50.71	5.4	0.9	0.36	0.67	−1.23
2	470	103	0.7	1.4	335	−5.76	0.01	−43.81	3.7	−4.0	0.42	1.25	−1.76
3	320	193	35	2	160	−5.58	0.03	−43.79	1.6	0.6	−0.21	−0.16	−1.53
4	1000	278	72	3.7	269	−5.56	0.02	−46.91	8.5	−0.1	0.15	0.86	−1.33
5	270	31	60	0.6	450	−5.97	0.02	−46.47	2.8	−0.3	0.31	0.89	−2.29
6	275	34	20	0.7	392	−5.5	0.03	−45.19	3.1	0.2	0.11	0.54	−2.31
7	87	8	37	0.4	217	−6.15	0.04	−48.67	6.0	6.4	0.38	0.91	−2.81
8	45	17	1	0.3				−34.28	4.8	0.1	0.17	0.54	−2.56
9	90	36	23	0.5	179	−4.86	0.03	−41.06	1.8	3.8	0.29	1.13	−2.51
10	370	270	67	1.6	231	−4.93	0.05	−37.36	7.0	5.0	0.19	0.66	−1.36
11	98	192	50	0.4	244	−5.64	0.06	−42.32	5.2	3.1	0.45	1.28	−1.82
12	205	186	0.1	0.6	341	−5.65	0.04	−40.24	3.9	−4.1	0.11	0.8	−1.95
13	2080	1160	45	5	415	−4.88	0.03	−35.69	8.3	−0.8	0.4	1.49	−0.6
14	10,500	4270	15	21	499	−4.99	0.03	−45.66	8.6	0.3	0.17	0.91	0.47
15	2600	760	71	6	432	−4.01	0.02	−36.72	1.5	−1.1	0.58	1.5	−0.42
16	1800	380	17	4			2.95	−42.08	5.4	0.8	0.3	0.79	−0.72
17	3100	608	91	12	258	−5.48	0.03	−36.84	5.0	−4.5	0.34	1.23	−0.7
18	2075	275	3	4	517	−5.38	0.04	−42.92	1.2	−7.2	−0.02	0.39	−1.13
19	1280	110	6	3	425	−5.27	0.04	−38.84	1.7	−6.1	0.05	0.37	−1.42

TW and HP refer to tubewell and hand-pump, respectively. EC, IBE and SI account for electric conductivity, ionic balance error and saturation index, respectively. Part of this data is also used in Lorenzen et al. (2012)

^a δ¹⁸O and δ²H are expressed in ‰ vs VSMOW

Fig. 3 Surface elevation and potentiometric data

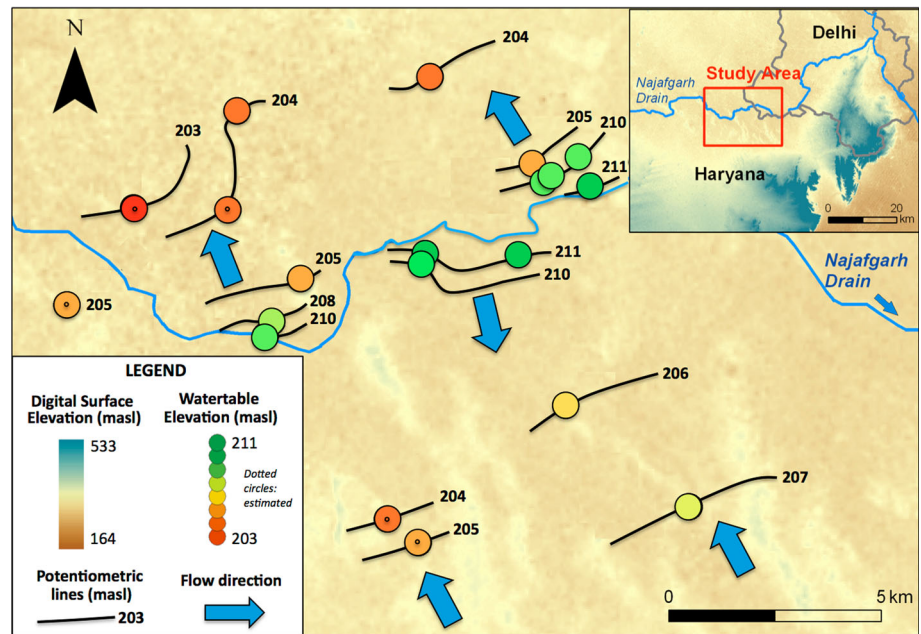
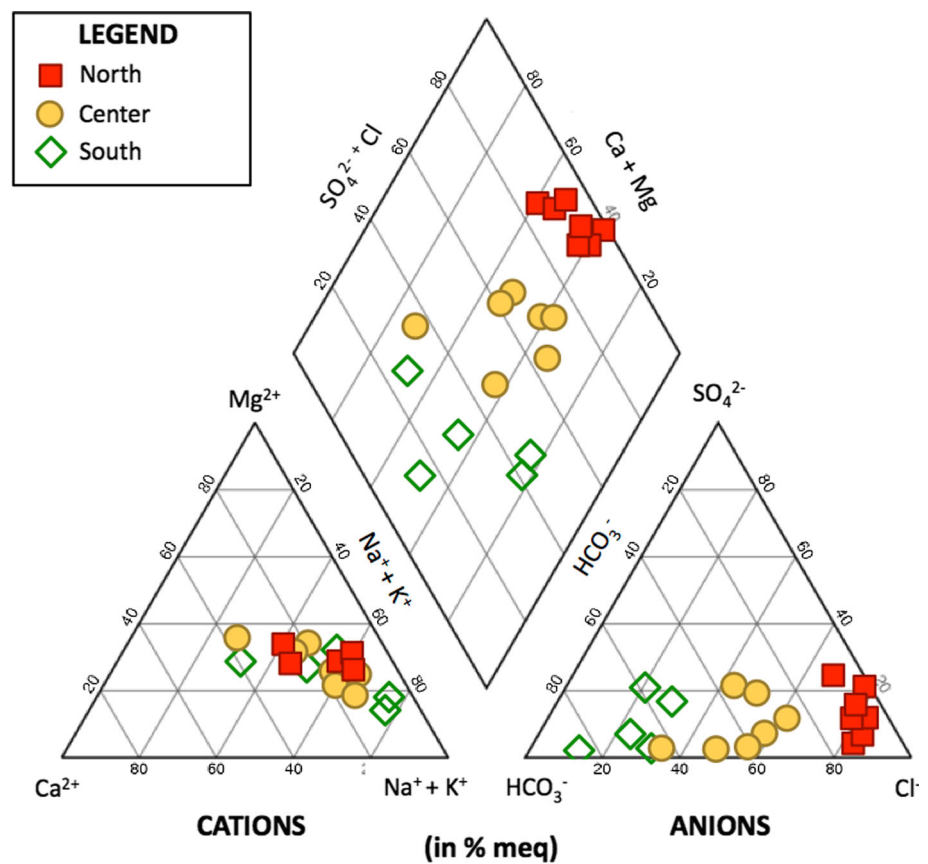


Fig. 4 Piper plot showing three different categories of groundwater corresponding to the southern, central and northern part of the area



between the September monsoon rainfall composition in Delhi and the enriched samples from the north and the south area. Mean monsoon isotope compositions were taken from data of the Global Network of Isotopes in

Precipitation (GNIP) from the New Delhi station. According to this data, the monsoonal compositions of rainfall in July are relatively enriched in heavy isotopes and become more and more depleted during monsoon. The

Fig. 5 Map of the study area including Stiff diagrams

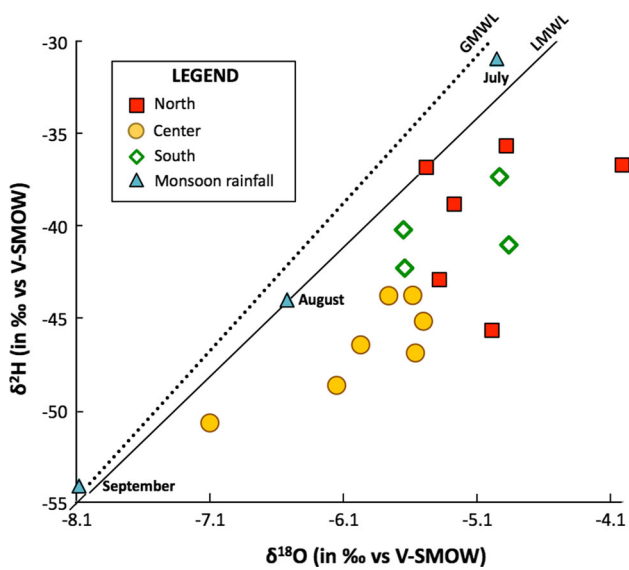
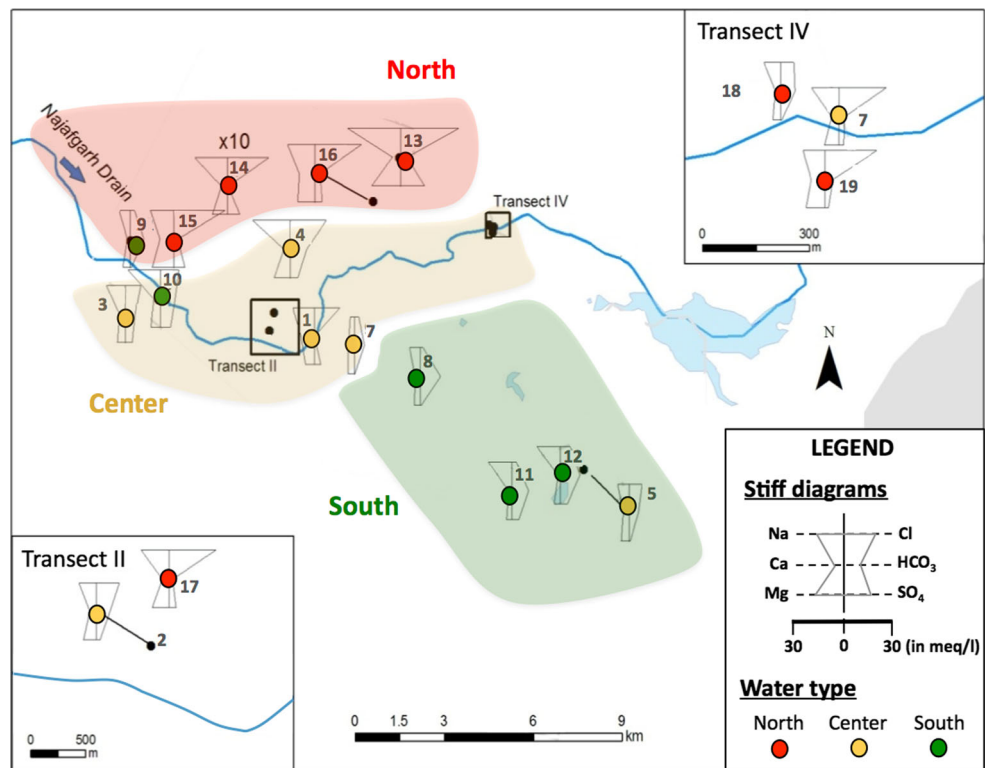


Fig. 6 $\delta^2\text{H}$ vs $\delta^{18}\text{O}$ diagram of groundwater samples showing the Global Meteoric Water Line (GMWL, dotted line after Craig 1961), the Local Meteoric Water Line (LMWL for Delhi, thin line, after Datta et al. 1991) and the monsoonal rainfall composition in New Delhi in July, August and September

range of mean monsoonal rain isotope composition is clearly reflected in the samples from the study area. This finding confirms that groundwater recharge mainly takes

place during monsoon, but undergoes substantial changes due to large deviations from the LMWL.

Discussion

As the hydrochemical data indicates, the three groundwater types reflect three distinct geographical areas: southward from the drain, northward from the drain, and along the drain. They reveal different geochemical processes and provide insights for characterizing the regional groundwater flow pattern, especially regarding the role of the drain. In addition, the origin of groundwater salinity is investigated.

Stable isotopes of water

The deviation of samples from the LMWL is likely to result from non-equilibrium fractionation during evaporation and mixing between isotope end-members. This effect is well illustrated by groundwater samples from the central area that link groundwater from northern and southern areas with an independent source whose composition is close to that of monsoon rainfall in September.

Groundwater samples from the southern area are closer to the LMWL and more uniformly distributed than samples from the north area. These samples, which are assumed to

represent isotope signatures from the recharge zone in the Aravalli hills, show a certain degree of evaporative enrichment. A conceptual interpretation may include water recycling by abstraction for irrigation, evaporative losses on the paddy fields, partial recharge (irrigation return flow) and subsequent re-abstraction further down gradient (towards the drain). This cycle of abstraction–evaporation–recharge may explain the isotope composition of this group. It is not possible to derive clear evaporation lines because the initial isotope composition for each groundwater sample seems to be different.

Groundwater samples from the northern area are largely scattered and sometimes far below the LMWL (max. 2 ‰ deviation in $\delta^{18}\text{O}$). This composition cannot be explained by water recycling through irrigation and recharge and it seems likely that mixing with other end-members occurs. Lorenzen et al. (2012) have characterized the deep, brackish to saline groundwater by isotopic composition of <-4.5 ‰ for $\delta^{18}\text{O}$. The authors conclude that dissolution of salts from deep geological formations (e.g., salt clays) may explain the elevated mineralization. While this brine end-member was not sampled in the study area, it seems likely that a highly mineralized and isotopically depleted groundwater mixes in the northern area.

Carbonate geochemistry

Except for sample 3, most samples are saturated to over-saturated with respect to calcite and dolomite (Table 2). This could be explained by: (1) the dissolution of primary carbonate minerals from the sediments, or (2) the presence of nodules of “kankar” in the Older Alluvium, a typical feature of the Ganga Plain (Singh and Singh 1972; Thussu 2006; Chandra et al. 2007). Also called caliche or calcrete, kankar is made of secondary calcium carbonates that can be formed close to the surface in the sediments by two processes: alluvial concentration of carbonates by pedogenetic processes in the “B” horizon of soil, and capillary rise and evaporation of CaCO_3 -charged groundwater during the hot and dry period. Kulkarni (1989) suggested that the development of intense kankar deposits took place mainly under an interpluvial climate in the Pleistocene. In the study area, where semi-arid climate limits pedogenesis, the water table increases after monsoon and decreases during the dry season. Thus, contemporaneous formation of Kankar, linked to precipitation/dissolution processes, could be more logically explained by the second option.

Ion exchange processes

Ion exchange is a common process during re-freshening or salinization of aquifers (Appelo and Postma 2005). Most samples from the southern area present depletion in Ca and

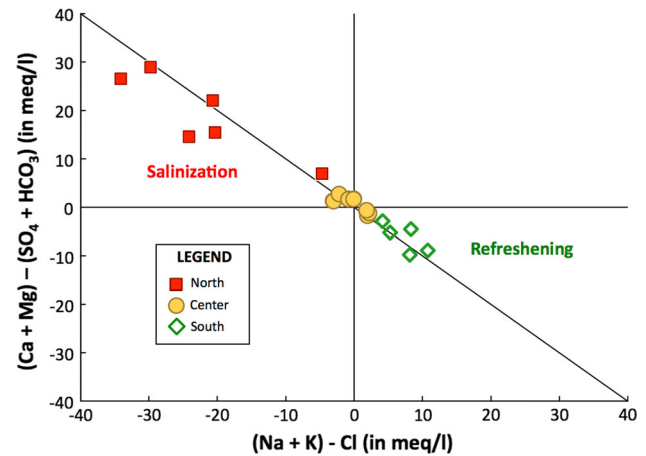
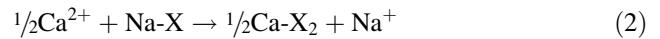
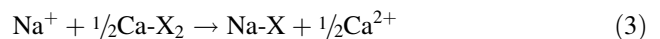


Fig. 7 Ion exchange diagram. For simplification, the value of sample 14, around $-60/60$ is not represented (see Table 2)

Mg compared to HCO_3^- and SO_4^{2-} and an excess of Na compared to Cl (Fig. 7). These characteristics are explained by a re-freshening through cation exchange reactions between Ca^{2+} and Na^+ , catching calcium ions on the exchanger and releasing sodium ions to the solution, as expressed by Eq. 2:



where X indicates the soil exchanger. This process typically occurs when freshwater (dominated by Ca^{2+} and HCO_3^- ions) flushes a salt water aquifer, where sediments in contact with salt water have adsorbed Na^+ for a large part, resulting in Na- HCO_3 type groundwater. This type of water is found predominantly in the southern part of the study area. When saline water intrudes in a fresh water aquifer, ion exchange process can be described by Eq. 3:

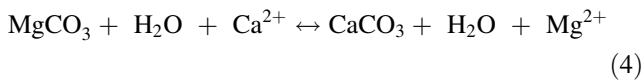


where Na is taken up by the binding sites of the exchanger and Ca is released into the water in return. The water type changes here from NaCl to CaCl_2 . This type of water is found predominantly in the northern part of the study area.

Here, as shown by Kumar et al. (2011), we can safely suppose that fresh water comes from the Ridge, located southward from the study area. The alteration of the plagioclases of the quartzitic rocks from the Ridge could be an additional source of dissolved sodium.

The high amount of Mg compared to Ca (Table 2) could be linked to the presence of Mg-calcite in the sediments. When a solution is in equilibrium with a mineral, permanent dissolution and precipitation reactions occur. Here, all samples are saturated with respect to calcite, which means that when Mg-calcite is dissolved, pure calcite precipitates,

and Mg^{2+} is released into the solution, as expressed by Eq. 4:



Dissolution of evaporites (north)

Samples from the northern area have a very similar HCO_3^- content (between 230 and 420 mg/l), and present an important excess of ($Ca^{2+} + Mg^{2+}$) compared to HCO_3^- and SO_4^{2-} (Fig. 7), showing that the dissolution of calcite and dolomite cannot be the only source for these cations. Indeed, as Table 2 indicates, the highest saturation indexes for anhydrite ($CaSO_4$) are found in the northern area, reaching up to 0.5 (sample 14). Accordingly, the above-mentioned excess in the northern area is partly caused by anhydrite, as a substantial additional source of Ca^{2+} . In addition, the (K + Na) -Cl relation (Fig. 7) shows a strong excess in Cl versus Na, indicating that groundwater from the northern area also dissolved halite.

The chloride/bromide relation can provide additional insights on the origin of salinity. Rainfall Cl/Br ratios are close to that of seawater with a weight ratio of 293 (Alcalá and Custodio 2008), despite some small deviations caused mainly by distance and pollution. When a solution dissolves halite, the Cl/Br becomes enriched, with weight ratio up to thousands (Alcalá and Custodio 2008). As Table 2 illustrates, samples from the northern area (except no. 17) have Cl/Br values from 415 to 517, with an average value of 428, which is notably higher than seawater. These waters correspond therefore to a mixing between saline water, having dissolved halite and fresh water deriving from infiltration. Groundwater from the central area shows an important scatter, with Cl/Br ratios between 160 and 450 (average value of 322). Two points show some possible influence of halite (samples 5 and 6). Even though it is located next to sand dunes, sample 3, has a low value of 160 that does not correlate with the presence of halite suggested by Subramayian and Saxena (1983) in such environment. Samples from the south (except sample 12) are mostly below the seawater value, with an average Cl/Br value of 198. These ratios are typical of inland fresh groundwater (Alcalá and Custodio 2008), due to enrichment in Br in rain-water compared to seawater. As Br is easily linked to organic matter, an additional explanation could be a change in the soil use, such as deforestation that may oxidize the organic matter, release Br in solution, and thus reduce the Cl/Br ratio to the observed values.

Infiltration of surface water and mixing (drain)

Samples from the central area are less mineralized than those from the southern and northern areas. They have a low-evolved geochemistry, as illustrated by Fig. 7. Groundwater in this area seems to interrupt the geochemical processes of the freshening of saline groundwater from the south. Groundwater recharge from the drain could therefore act as a hydraulic barrier for groundwater originating from the southern area.

This interpretation is strengthened by two independent approaches. As Fig. 6 shows, groundwater from the central area has an isotopic signature distributed along a mixing line between the ambient groundwater (i.e., northern + southern areas) and another source whose composition is close to that of the September monsoon. Therefore, groundwater from the central area is not a simple mixing between northern and southern groundwater, but receives a significant contribution of geochemically low-evolved water located at the Najafgarh drain. Secondly, the groundwater table elevation map (Fig. 3) confirms: (1) the presence of a regional groundwater flow from the Delhi Ridge, and (2) loosing conditions of the drain, even during the dry season. Thus, an active and consistent recharge from the Najafgarh drain to the aquifer is occurring in this eastern part of the Haryana region despite the low availability of surface water and the low hydraulic conductivity of the riverbed. Only further east, downstream the weir at the Delhi border, surface water-groundwater interaction is dominated by drainage of the land and gaining river conditions most of the year (Lorenzen et al. 2010).

Conclusions

The aim of this investigation was to characterize the groundwater flow pattern in a rural area of Haryana, India, with a special focus on groundwater recharge from an intermittent monsoon-controlled watercourse, the Najafgarh drain, using geochemical, isotopic and potentiometric data.

An important hydrogeochemical zonation between the southern and the northern parts of the area was observed. Southward from the drain, fresh groundwater was found (electrical conductivity between 0.5 and 2.3 mS/cm) with a dominant Na- HCO_3 water type. Mineralization revealed strong cation exchange processes, primarily explained by the flushing of saline groundwater by fresh groundwater originating from the Aravalli hills. Northward from the

drain, groundwater was moderately to highly saline (electrical conductivity from 4.1 to 23.4 mS/cm) and the dominant water type was Na-Cl. Mineralization indicated the presence of water having dissolved evaporates, mostly halite and gypsum. In the vicinity of the drain, salinity was intermediate (0.7–4 mS/cm) and groundwater geochemistry was much less evolved, leading to the hypothesis of a significant recharge from the drain. Isotopic data correlated this assumption by revealing the critical input at the drain of water having the isotopic composition of monsoon rainfall (September). Finally, potentiometric data provided additional evidence and led to the conclusion that the drain acts as a hydraulic barrier for groundwater between the southern and the northern parts of the area. Therefore, in this specific area, the Najafgarh drain significantly contributes to the recharge of the aquifer despite the limited recharge potential, restricted by the availability of monsoonal flood-water and the low hydraulic conductivity of the banks.

By providing a special insight on the impact of an intermittent watercourse on groundwater recharge, this study demonstrates the value of hydrogeochemical and isotopic data for characterizing groundwater flow pattern in anthropized agricultural areas with scarce discharge. Further investigation on the quantification of recharge from the drain to the aquifer should focus on the evolution of the system before, during and after monsoon. More specifically, a notable state forward regarding the quantification of the spatiotemporal variability of recharge would be attained by using environmental time tracers.

Acknowledgments This study was carried out within the framework of the EU integrated project TECHNEAU (work package 5.2) with scientific mentoring by Prof. A. Pekdeger (†) at Freie Universität Berlin. Thanks to Yann Moreau-Le Golvan, Janek Greskowiak and Gesche Grütmacher from Kompetenzzentrum Wasser Berlin for their support in project management and logistics. This study is a result of collaboration between Kompetenzzentrum Wasser Berlin, the Indian Institute of Technology and Freie Universität Berlin.

References

- AGC (2001) Report on evaluation study of soil conservation in seven watersheds of Sahibi catchment in Haryana and Rajasthan. Report. Agricultural Finance Corporation, Sponsored by the Ministry of Agriculture, India, New Delhi
- Alcalá FJ, Custodio E (2008) Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and in Portugal. *J Hydrol* 359(1–2):89–207
- Appelo CAJ and Postma D (2005) *Geochemistry, groundwater and pollution*, 2nd edn. AA Balkema Publishers, Rotterdam, The Netherlands
- Baudron P (2008) Hydrochemical characterization of groundwater and estimation of recharge from the Najafgarh drain, South-West of Delhi, India. Unpublished Dissertation. Université Paris Sud, Orsay, France
- Baudron P, Alonso-Sarria F, García-Aróstegui JL, Cánovas-García F, Martínez-Vicente D, Moreno-Brotóns J (2013) Identifying the origin of groundwater samples in a multi-layer aquifer system with random forest classification. *J Hydrol* 499:303–315. doi:10.1016/j.jhydrol.2013.07.009
- Baudron P, Barbécot F, Aróstegui JLG, Leduc C, Travi Y, Martínez-Vicente D (2014) Impacts of human activities on recharge in a multilayered semiarid aquifer (Campo de Cartagena, SE Spain). *Hydrol Process* 28:2223–2236. doi:10.1002/hyp.9771
- Brindha K, Kavitha R (2014) Hydrochemical assessment of surface water and groundwater quality along Uyyakondan channel, south India. *Environ Earth Sci*. doi:10.1007/s12665-014-3793-5
- CGWB—Central Ground Water Board of India (2006) Ground water year book 2005–2006, National Capital Territory, Delhi. Government of India, Ministry of Water Resources, New Delhi
- Chandra S, Rhodes E, Richards K (2007) Luminescence dating of late Quaternary fluvial sediments in the Rapti Basin, north-central Gangetic Plains. *Quatern Int* 159(1):47–56
- Craig H (1961) Isotopic variations in meteoric waters. *Science* 133:1702–1703
- Custodio E (2002) Aquifer overexploitation: what does it mean? *Hydrogeol J* 10:254–277. doi:10.1007/s10040-002-0188-6
- Datta PS, Tyagi SK, Chandrasekharan H (1991) Factors controlling stable isotopic composition of rainfall in New Delhi. *J Hydrol* 128:223–236
- Dwivedi AK, Vankar PS, Sahu RS (2015) Geochemical trends of heavy metal in aquifer system of Kanpur Industrial Zone, Uttar Pradesh (India): a case study. *Environ Earth Sci*. doi:10.1007/s12665-015-4017-3
- Flood Control Wing (1976) Master plan for drainage of storm water drainage of the Najafgarh basin in Union Territory of Delhi. Master Plan Organization, Delhi Administration
- Katpatal YB, Pophare AM, Lamsoge BR (2014) A groundwater flow model for overexploited basaltic aquifer and Bazada formation in India. *Environ Earth Sci* 72:4413–4425. doi:10.1007/s12665-014-3342-2
- Kulkarni KM et al (1989) “Origin of saline groundwaters of Haryana State, India”, Regional Characterization of Water Quality (Proceedings of the Baltimore Symposium, May 1989). IAHS Publication no. 182, Wallingford, pp 125–129
- Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environ Geol* 50(7):1025–1039
- Kumar M, Rao MS, Kumar B, Ramanathan A (2011) Identification of aquifer-recharge zones and sources in an urban development area (Delhi, India), by correlating isotopic tracers with hydrological features. *Hydrogeol J* 19:463–474. doi:10.1007/s10040-010-0692-z
- Lorenzen G, Sprenger C, Taute T, Pekdeger A, Mittal A, Massmann G (2010) Assessment of the potential for bank filtration in a water-stressed megacity (Delhi, India). *Environ Earth Sci* 61:1419–1434. doi:10.1007/s12665-010-0458-x
- Lorenzen G, Sprenger C, Baudron P, Gupta D, Pekdeger A (2012) Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and adjacent territories of Haryana State, India. *Hydrol Processes* 26:2333–2345
- Massuel S, Perrin J, Wajid M, Mascré C, Dewandel B (2009) A Simple. Low-cost method to monitor duration of ground water pumping, ground water 47:141–145. doi:10.1111/j.1745-6584.2008.00511.x
- Massuel S, George BA, Venot JP, Bharati L, Acharya S (2013) Improving assessment of groundwater-resource sustainability with deterministic modelling: a case study of the semi-arid Musi sub-basin, South India. *Hydrogeol J* 21:1567–1580. doi:10.1007/s10040-013-1030-z

- Mohan I (2007) Environment education. APH Publishing Corporation, Daryaganj, India
- Murkute YA (2014) Hydrogeochemical characterization and quality assessment of groundwater around Umrer coal mine area Nagpur District, Maharashtra, India. *Environ Earth Sci* 72:4059–4073. doi:10.1007/s12665-014-3295-5
- Nema A, Agarwal L (2003) Wastewater management in Najafgarh drainage basin: a key to water quality improvement in river Yamuna. Indian Association of Environment Management, Annual Conference, New Delhi. <http://www.greenensys.org/site/publications/Wastewater%20management%20in%20Najafgarh%20drainage%20basin.pdf>. Accessed 28 Dec 2014
- Perrin J, Ahmed S, Hunkeler D (2011) The effects of geological heterogeneities and piezometric fluctuations on groundwater flow and chemistry in a hard-rock aquifer, southern India. *Hydrogeol J* 19:1189–1201. doi:10.1007/s10040-011-0745-y
- 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* 122:43–54. doi:10.1007/s12040-012-0256-9
- Singh L, Singh S (1972) Chemical and morphological composition of kankar nodules in soils of the Vindhyan region of Mirzapur, India. *Geoderma* 7(3–4):269–276
- Subramayian V, Saxena KK (1983) Hydrogeochemistry of groundwater in the Delhi region of India, Relation of Groundwater Quantity and Quality (Proceedings of the Hamburg Symposium, August 1983. IAHS Publication no. 146
- Thussu JL (2006) Geology of Haryana and Delhi. Geological Society of India, Bangalore, India