Effects of rainwater-harvesting-induced artificial recharge on the groundwater of wells in Rajasthan, India

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Abstract In light of the increasing deterioration of groundwater supplies in Rajasthan, India, rainwater harvesting practices in southern Rajasthan were studied to determine the effects of artificially recharged groundwater on the supply and quality of local groundwater. A physical and geochemical investigation utilizing environmental tracers ($\delta^{18}O$ and Cl^-), groundwater level and groundwater quality measurements, and geological surveys was conducted with two objectives: (1) to quantify the proportion of artificially recharged groundwater in wells located near rainwater harvesting structures and (2) to examine potential effects of artificial recharge on the quality of groundwater in these wells. A geochemical mixing model revealed that the proportion of artificial recharge in these wells ranged from 0 to 75%. Groundwater tracer, water table, and geological data provided evidence of complex groundwater flow and were used to explain the spatial distribution of artificial recharge. Furthermore, wells receiving artificial recharge had improved groundwater quality. Statistical analysis revealed a significant difference between the water quality in these wells and wells determined not to receive artificial recharge, for electrical conductivity and SO_4^-. The findings from this study provide quantitative evidence that rainwater harvesting structures in southern Rajasthan influence the groundwater supply and quality of nearby wells by artificially recharging local groundwater.

Keywords Rainwater harvesting · Artificial recharge · Water quality · Tracer tests · India

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Introduction

With changing climate and growing levels of water consumption, increasing seasonal variability and steady declines in groundwater levels pose a problem of access to reliable water supplies for many of India's rural inhabitants. Rajasthan, one of India's driest states, relies on groundwater for 90% of its drinking water supply and 60% of its water for irrigation (ECIDWR 2005). This heavy dependence on groundwater arises from sparse surface water supplies. Rajasthan is India's largest state, with more than 10% of the country's geographic area and 5% of India's population, yet it contains only 1% of the nation's total surface water resources (GOR 2005). Overexploitation of groundwater resources throughout the state has led to only 32 of the 236 "blocks" (subdistricts) in Rajasthan to be considered safe with respect to groundwater consumption (Sharma and Roy 2003).

In recent decades, rainwater harvesting (RWH) has been promoted as a solution to the overexploitation of the Rajasthan's groundwater resources (Kumar et al. 2005). Rainwater harvesting is defined as the collection and

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storage of rainwater in surface or sub-surface reservoirs as a means to reduce the amount of water lost to storm runoff and evaporation (CGWB 2003). Efforts to harvest rainwater are currently being employed in many arid and semi-arid regions throughout the world in order to sustain agriculture and general water supply. Rainwater harvesting was first documented in the Mediterranean region, ca. 4,000 years ago (Joshi 2002); archeological evidence reveals that RWH activities have been central to indigenous civilizations in India for the past 2,000 years (Gunnell et al. 2007). A key strength of RWH is that it is a decentralized and indigenous water management strategy that can be easily implemented in many rural settings. An important objective of many RWH techniques is to artificially recharge groundwater. Artificial recharge, as defined by the Central Ground Water Board (CGWB) of India, is a process of augmenting a groundwater reservoir at a rate that exceeds natural conditions of replenishment (CGWB 2003).

In light of the overexploitation of groundwater resources resulting from modern extraction techniques, there has been a resurgence of traditional RWH activities in India in recent decades (Sharma 2002), with Rajasthan acting as a cradle of this rural water-management revival (Kumar et al. 2005). Substantial investments have been made to promote RWH activities in Rajasthan among government, non-government, and private sectors (Samantaray 1998; ECIDWR 2005). Much of the focus of these efforts has been on the artificial recharge potential of RWH (Patel 1997). It is commonly assumed that these RWH practices artificially recharge local groundwater and increase the water level in wells located near these structures. This suspected increase in the water level of traditional rural wells would buffer seasonal and inter-annual declines in groundwater, thereby improving access to reliable water supplies.

Although substantial RWH efforts have been carried out in Rajasthan, very few studies have systematically investigated their actual artificial recharge potential in a scientific manner (Rathore 2005). As a result, many RWH structures are built without a clear understanding of their effect on the local groundwater system. Further, much of the investment made into RWH cannot be properly scrutinized. In light of this knowledge gap, a detailed physical and geochemical investigation was carried out in the Wakal River Basin (southern Rajasthan) to determine the impact of RWH structures on improving rural water supply in nearby wells. This study had two primary objectives: (1) to quantify the proportion of artificially recharged groundwater in wells adjacent to RWH structures and (2) to examine potential effects of artificial recharge on the groundwater quality in these wells.

Study area

The Wakal River Basin lies between the latitudes of 24.15 and 24.78°N and the longitudes of 73.11 and 73.60°E and covers 1,900 km^2 of the southern region of the State of Rajasthan, India (Fig. 1). The Wakal River originates at an elevation of 762 m in the Aravalli Hills and is the source of the larger Sabarmati River, which flows 371 km through the Indian States of Rajasthan and Gujarat before discharging into the Gulf of Cambay in the Arabian Sea (ICID 2005). The 300,000 inhabitants of the Wakal River Basin live predominantly in rural settlements and agriculture is the primary land use and consumer of water (ICID 2005).

The Wakal River Basin has a tropical monsoon climate with an average annual temperature of 26°C. Average annual rainfall is 650 mm (GOR 2002), with approximately 30 rainy days per year, occurring almost entirely during the monsoon season of late June to October (Mahnot and Singh 2003). Rainfall in the basin is highly variable inter-annually, and droughts occur frequently (Moench et al. 2003).

The hydrogeology of the Wakal River Basin is dominated by hard rock aquifers of igneous and metamorphic rock (Moench et al. 2003). These aquifers are unconfined and have low transmissivity values ranging from 20–100 m^2/day (Kumar et al. 1999). The depth of the aquifers is unknown, due to the remote location of the basin and the general absence of previous scientific investigation. The predominant rock types are garnet-mica schist, phyllite, and quartzite. Variations in hydrogeology are controlled mainly by the region's structural geology (Chauhan et al. 1996). Due to the lack of primary porosity in the rock types present, groundwater flow is controlled primarily by the presence of fractures.

Check dams are the predominant RWH technique in the basin. These structures take advantage of the mountainous terrain and collect monsoon storm runoff that would otherwise leave the basin rapidly. Check dams come in various types and sizes; the two most common are the *anicut* and the *nadi* (Fig. 2). The *anicut* is a small to medium-scale masonry dam and the *nadi* is a medium to large-scale earthen embankment dam. Both are constructed to impound ephemeral streams. When full of water, these structures have the dual purpose of providing additional surface water supplies, as well as recharging groundwater through the infiltration of impounded water (MNIT/UNICEF 2003).

This study focused on two study sites within the Wakal River Basin (Fig. 3). A study site in the village of Jharapipla comprised two RWH structures in series along the same stream. The primary RWH structure was a *nadi*, with a much smaller *anicut* located 800 m downstream. The second study site in the village of Godawara contained two *anicuts*, also in series along the same stream. At each study site, a number of open wells were positioned both upstream and downstream of each RWH structure. The naming of sample locations indicates the study site, the sample type, and the relative position of the sample location relative to the other sample locations (Table 1).

Methods

Field methods

Chloride (Cl$^-$) concentration and stable isotope ratios of oxygen (δ^{18}O) are widely utilized environmental tracers used to determine the relative contribution of both natural and artificial recharge sources to groundwater (Sukhija et

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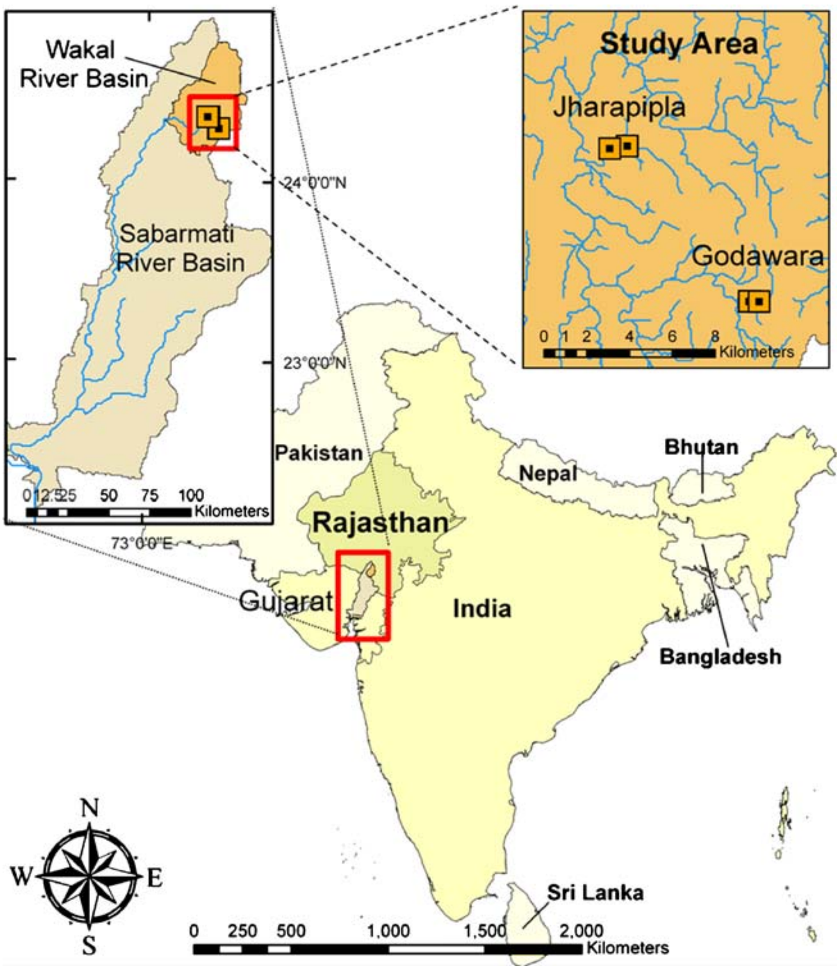

Fig. 1 Location of study area in the Wakal River Basin, southern Rajasthan, India. The two study sites were located in the villages of *Jharapipla* and *Godawara*. (India/Pakistan boundary as promulgated in the 1972 SIMLA Agreement)

al. 1997; Kendall and Caldwell, 1998; Ojiambo et al., 2001). A total of 69 water samples were collected from May–July 2006 for Cl^- (mg/l) and $\delta^{18}O$ analyses. Water samples were collected at the beginning, middle, and end of the study period from 16 wells, four RWH structures, and two rainfall collection stations (Table 1). Water samples were collected in sterile, sample-washed, 125 ml high-density polyethylene (HDPE) bottles and required no special preservation. Groundwater samples were collected from open wells within the study sites; the depths of these wells varied from 1.8–11.7 m, with an average diameter of 5 m. Rainfall collectors were prepared to collect rainwater samples for isotope analyses; dark brown 2-l HDPE collection bottles were equipped with a funnel and sealed with a stopper. Inside the bottle, a loop made of rubber tubing provided a vapor lock in order to prevent evaporation (Price and Swart 2006).

Groundwater levels were monitored in 15 wells over the study period using a Solist depth-to-water meter (Table 1). The depth to groundwater was then subtracted from the elevation recorded with a Magellan Meridian global positioning system (GPS) to quantify the water table in meters above mean sea level. The interpolated water table surface for each study site was derived from the average groundwater levels. Spatial interpolations were performed using the commonly utilized Kriging method (Gundogdu and Guney 2007).

A survey of the structural geology was carried out for each study site. A clinometer was used to determine the strike of the fractures, along with the dip angle and direction. These measurements were made at exposed rock outcrops present at the study sites. The location of each outcrop was recorded with a GPS receiver. The data were brought into a geographic information system (GIS) in order to generate digital maps.

Additional groundwater samples were collected for water quality analysis from select wells located both upstream and downstream of the RWH structures. This sampling strategy was based on the assumption that groundwater would flow in the downstream direction, following local topography. A total of five wells were sampled twice during the study period: once before the arrival of the monsoon and once during the monsoon. For each well, water-quality samples were collected for laboratory analysis. Additionally, electrical conductivity

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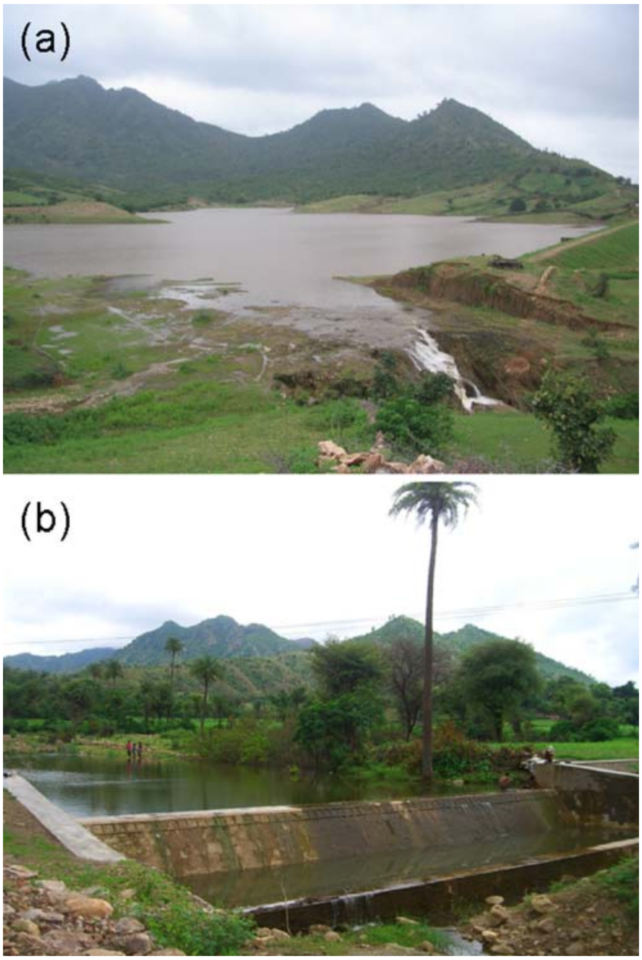

Fig. 2 Rainwater harvesting (RWH) structures: **a** *nadi* and **b** *anicut*. These RWH structures are located in the village of Jharapipla

(EC) was measured weekly at each of the sampling locations using a Thermo Russell RL060C conductivity/temperature meter.

Laboratory methods

The oxygen isotopic composition of the tracer samples was measured in the Stable Isotope Laboratory at the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences (Miami, Florida, USA). The δ^{18}O measurements were made in duplicate; the method for the measurement of δ^{18}O was a modification from the conventional techniques using a Europa GEO dual-inlet mass spectrometer (Swart 2000). All data were calibrated using Vienna Standard Mean Oceanic Water (VSMOW) and are reported in parts per thousand (‰) according to conventional notation.

Laboratory analysis for chloride and sulfate was carried out in the Hydrogeology Laboratory at Florida International University (Miami, Florida, USA). Chloride and sulfate concentrations were determined on a Dionex 120 ion chromatographer. Water-quality samples were analyzed for pH, alkalinity, total hardness, calcium hardness, magnesium hardness, total dissolved solids, sulfate, nitrate, and fluoride in the Sanitation, Water, and Community Heath (SWACH) Water Quality Laboratory, Udaipur, Rajasthan, India.

Geochemical mixing model

Once groundwater is no longer subject to evaporation, both δ^{18}O and Cl^- (mg/l) act as conservative groundwater tracers, which maintain their tracer signatures until they mix with waters of different δ^{18}O and Cl^- (mg/l) levels (Kendall and Caldwell 1998). These tracers also mix conservatively and are ideal for tracking the movement of water through the environment (Genereux 2004). In the case where two waters with distinct isotopic compositions become well mixed, the resulting mixture will fall along a line with the two end-members comprised of the isotopic compositions of the original waters (Kendall and Caldwell 1998). The relative proportion of each end-member can then be quantified by a simple mixing model.

An example of three unique signatures of groundwater mixing conservatively is seen in the simple relationship of Eq. (1). In this equation, x, y, and z represent the fraction of each of the three unique tracer signatures of water, or end-members, in the resulting mixture of groundwater. The sum of the fraction of each end-member accounts for 100% of the water in the resulting mixture. The relationship in Eq. (1) can be applied to δ^{18}O and Cl^- in Eqs. (2) and (3), respectively. The variables x, y, and z represent the fraction of each unique end-member, as they did in Eq. (1); however, the tracer signature is restricted to δ^{18}O in Eq. (2) and Cl^- in Eq. (3). This same principle is described graphically by Eby (2004).

$$1 = x + y + z \tag{1}$$

$$\delta^{18}O_{\text{sample}} = \delta^{18}Ox+\delta^{18}Oy + \delta^{18}Oz \tag{2}$$

$$Cl^-_{\text{sample}} = Cl^-x + Cl^-y + Cl^-z \tag{3}$$

The sources of the groundwater in each sampled well, along with the proportion of each groundwater source, were estimated using a three-end-member geochemical mixing model (Eby 2004). Variations in Cl^- (mg/l) and δ^{18}O levels among the water samples were used to describe and identify groundwater end-members at the study sites (Douglas et al. 1999). End-member signatures were empirically evident when the average Cl^- and δ^{18}O values were plotted graphically against each other. Subsequently, the average Cl^- and δ^{18}O values for the remaining samples were plotted graphically and the fraction of each identified groundwater end-member was determined using fundamental geometric ratios. Additional information on this method can be found in Eby (2004).

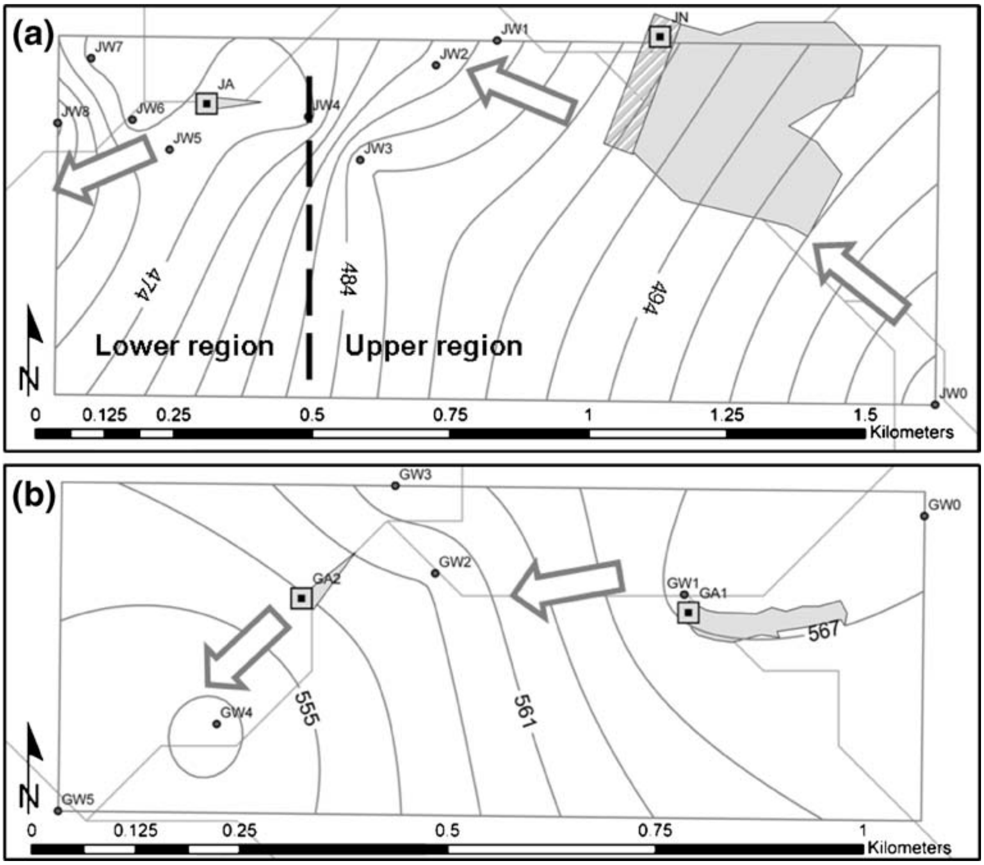

Fig. 3 Average water-table elevation (m) at the study sites: **a** Jharapipla and **b** Godawara. *Arrows* represent inferred groundwater flow direction: upstream to downstream. *Contour lines* represent water table; *double squares* signify RWH structures; *polygons* signify impounded surface water; *points* signify sampled wells; *light grey lines* signify streams. The *thick dashed line* signifies division between the upper and lower regions of the Jharapipla study site

Table 1 Average tracer and water level data for each sample location over the study period

Site	Description	$\delta^{18}O$ (‰ VSMOW)		Cl^- (mg/l)		Water Level (m asl)
JW0	Jharapipla well (located upstream of JN)	–5.36	(0.26)	76.47	(5.49)	505
JN	Jharapipla *nadi* (upper region)	–3.42	(0.16)	15.61	(0.92)	
JW1	Jharapipla well (first downstream of JN)	–3.89	(0.24)	44.84	(1.80)	483
JW2	Jharapipla well (second downstream of JN)	–4.20	(0.12)	68.38	(3.30)	481
JW3	Jharapipla well (third downstream of JN)	–2.65	(0.02)	183.32	(11.49)	486
JW4	Jharapipla well (fourth downstream of JN)	–5.30	(0.34)	92.51	(1.64)	473
JA	Jharapipla *anicut* (lower region)	–3.29	(0.05)	40.59	(8.84)	
JW5	Jharapipla well (first downstream of JA)	–3.83	(0.80)	111.06	(14.20)	473
JW6	Jharapipla well (second downstream of JA)	–3.27	(0.44)	79.18	(9.20)	475
JW7	Jharapipla well (third downstream of JA)	–3.89	(0.03)	50.06	(1.48)	475
JW8	Jharapipla well (fourth downstream of JA)	–2.91	(0.19)	143.71	(4.02)	465
JR	Jharapipla rainfall	–5.08	(1.44)	1.89	(0.83)	
GW0	Godawara well (located upstream of GA1)	–4.15	(0.10)	159.68	(5.97)	567
GA1	Godawara upstream *anicut*	–1.86	(3.66)	59.51	(40.09)	
GW1	Godawara well (first downstream of GA1)	–2.23	(1.04)	197.81	(35.70)	568
GW2	Godawara well (second downstream of GA1)	–4.41	(0.03)	46.44	(1.43)	559
GW3	Godawara well (third downstream of GA1)	–3.15	(1.28)	43.51	(15.27)	562
GA2	Godawara downstream *anicut*	–4.89	(0.23)	20.51	(11.73)	
GW4	Godawara well (first downstream of GA2)	–1.67	(0.57)	148.24	(12.79)	552
GW5	Godawara well (second downstream of GA2)	–4.07	(0.16)	102.38	(6.37)	555
GR	Godawara rainfall	–4.58	(0.97)	1.70	(0.05)	
GBW	Godawara bore well (deep groundwater)	–4.15		253.21		

Standard error is given in parentheses. *VSMOW* Vienna Standard Mean Ocean Water

Stiefel (2007) provides comprehensive data. Site locations are listed in order from upstream to downstream. Wells within a village are numbered serially from upstream to downstream. Water level is given in units of meters above sea level (m asl)

Results and discussion

The results of this study provide a quantitative description of the effect of artificial recharge induced by RWH on the water supply of adjacent wells of the remote Wakal River Basin, India. This study effectively utilized data generated from a combination of physical and geochemical tools: groundwater level data, geological survey data, groundwater tracer data, and groundwater chemistry data. Due to a lack of existing data in the relatively unstudied region, the findings of this study are based on data collected during 3 months of field work.

Regional groundwater flow direction

Water level data give insight into the regional groundwater flow direction at the study sites. The general trend reflected in the water-table surface at the study sites was a uniform decrease in the hydraulic head over the length of the sites, following general topography. Average groundwater levels varied by 40 m at Jharapipla, ranging from 505 meters above sea level (m asl) in the most upstream well to 465 m asl in the most downstream well (Fig. 3). Similarly, average groundwater levels varied by 15 m at Godawara, ranging from a high of 567 m asl at the upper region of the site to a low of 552 m asl in the downstream region. These data are useful to RWH efforts because they provide evidence of the general direction that water will likely travel if recharged from RWH structures, from a high water level to low water level. Since the RWH structures are consistently located upstream of numerous wells, any artificially recharged water is expected to flow toward the downstream wells, augmenting groundwater at these access points.

Evidence of artificial recharge in wells

The use of Cl^- (mg/l) and $\delta^{18}O$ as groundwater tracers indicate the source and proportion of groundwater in wells adjacent to RWH structures. Average Cl^- and $\delta^{18}O$ data from each sample location within the study sites are plotted together to identify distinct end-members that contribute to the groundwater present in each sampled well (Figs. 4, 5 and 6). Douglas et al. (1999) recognizes Cl^- and $\delta^{18}O$ as the dominant variables to describe similar three end-member mixing of groundwater. The average tracer values in our study were assumed to be more representative of the tracer signatures for each location than data from any individual sampling date during the study period. Due to a substantial difference in the scale of the RWH structures and the numerous observation wells present at the site, the Jharapipla study site is divided into two sub-sections for the sake of discussion. The upper region represents the upstream section and the *nadi*, while the lower region represents the downstream section and the *anicut*.

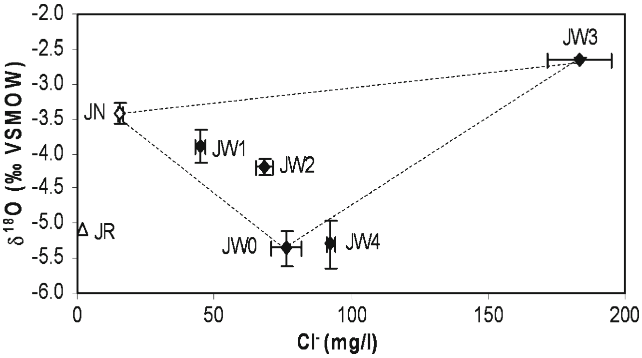

Fig. 4 Three end-member mixing of groundwater in Jharapipla (upper region), with respect to $\delta^{18}O$ and Cl^-. Groundwater in this region of the study site is comprised of a mixture of three distinct waters: (1) artificially recharged surface water from the RWH structure (*JN*); (2) background naturally recharged groundwater (*JW0*); and (3) enriched local groundwater (*JW3*). *Error bars* represent standard error

Jharapipla: upper region

The average $\delta^{18}O$ and Cl^- values in the upper region of Jharapipla range from –5.36 to –2.65‰ and 15.61 to 183.32 mg/l, respectively, and reveal three end-member signatures of water (Table 1; Fig. 4). The first is the surface water impounded behind the *nadi* (JN). This water is distinguished by low Cl^- (15.61 mg/l) and moderately elevated $\delta^{18}O$ (–3.42‰). A relatively low Cl^- value is expected, since the source of this water is recent monsoon rainfall. Sukhija et al. (2005) recorded the weighted-average Cl^- concentration of a similar RWH structure to be 11.5 mg/l. An elevated $\delta^{18}O$ composition is indicative of an evaporated surface water supply (Sukhija et al. 2006). Although exposure to evaporation will impact the tracer signature of both Cl^- and $\delta^{18}O$, changes in the isotopic composition of water are more sensitive than changes in chloride.

The second end-member water signature is groundwater from the well located upstream of the *nadi* (JW0). This water has a moderate Cl^- concentration (76.47 mg/l), with a very

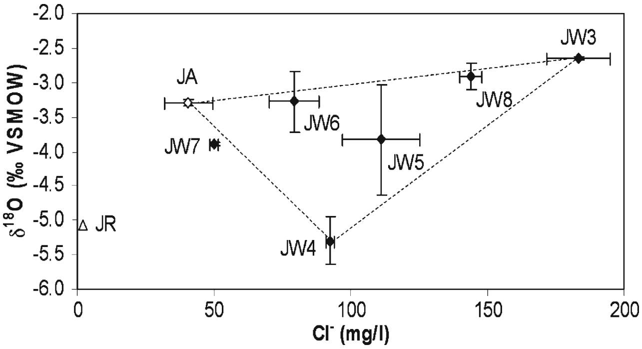

Fig. 5 Three end-member mixing of groundwater in Jharapipla (lower region), with respect to $\delta^{18}O$ and Cl^-. Groundwater in this region of the study site is comprised of a mixture of three distinct waters: (1) artificially recharged surface water from the RWH structure (*JA*); (2) background naturally recharged groundwater (*JW4*); and (3) enriched local groundwater (*JW3*). *Error bars* represent standard error

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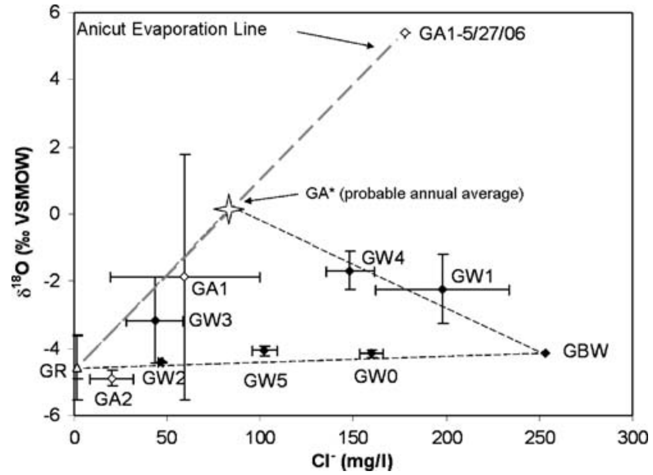

Fig. 6 Three end-member mixing of groundwater in Godawara, with respect to δ^{18}O and Cl$^-$. Groundwater in this study site is comprised of a mixture of three distinct waters: (1) artificially recharged surface water from the RWH structures (*GA**); (2) recent naturally recharged groundwater (*GR*); and (3) deep groundwater (*GBW*). *Error bars* represent standard error

low δ^{18}O composition (–5.36‰). The signature of this well is indicative of groundwater that is naturally recharged. A groundwater tracer study in central India has categorized naturally recharged groundwater as having a relatively low δ^{18}O composition and Cl$^- \leq 100$ mg/l (Sukhija et al. 2006). Our description of the second groundwater end-member is consistent with the findings of this previous study. The low δ^{18}O composition reflects rapid infiltration customary of natural recharge, while the moderately elevated Cl$^-$ concentration suggests a longer contact time with the geology and a wider area of recharge. The location of this well, approximately 400 m upstream of the *nadi*, suggests that it is not influenced by artificial recharge from the *nadi*. The general groundwater flow direction derived from the water table data supports this assumption. Therefore, the water signature in this well is considered to represent background groundwater that is entirely naturally recharged.

The third end-member signature present in the upper region of Jharapipla is groundwater sampled from the third downstream well (JW3). This water signature is characterized by high Cl$^-$ (183.32 mg/l) and relatively elevated δ^{18}O (–2.65‰). Although this water signature was unexpectedly enriched with respect to both Cl$^-$ and δ^{18}O, it is assumed to reflect a localized pocket of enriched groundwater. Many factors were investigated in an attempt to better understand this local phenomenon, including depth to groundwater, distance from wells to the nearby stream, and significantly different groundwater flow paths between each well; however, no substantial conclusions could be drawn from the available data. Since this study is essentially the first of its kind in the study area, pre-existing hydrogeological data are quite scarce. Although the water in this well is relatively enriched compared to surrounding wells, groundwater studies in the neighboring State of Uttar Pradesh, as well as the States of Andhra Pradesh and Tamil Nadu reveal Cl$^-$ concentrations of groundwater in excess of those recorded in this well (Umar and Ahmed 2007; Rao et al. 2007; Pandian and Sankar 2007). The unique groundwater signature evident in JD3 presents itself as a third distinct end-member within the groundwater at the site.

Most of the groundwater samples from the upper region of Jharapipla (JW1, JW2, and JW4) lie very near a binary mixing line between the harvested rainwater (JN) and the background groundwater (JW0; Fig. 4). Along this mixing line, a uniform pattern is present. The signature of the downstream well nearest to the *nadi* (JW1) most closely resembles the water in the *nadi*, and as the distance downstream of the *nadi* increases, well water increasingly resembles background groundwater. Upon reaching the fourth downstream well (JW4), a distance of 655 m downstream of the *nadi*, the groundwater closely resembles background groundwater, suggesting that this well is not recharged by the *nadi* upstream. These data imply that JW4 represents the downstream spatial limit of influence that artificially recharged water from the *nadi* has on the nearby groundwater field. This same groundwater spatial pattern with respect to Cl$^-$ has been observed in wells located downstream of a comparable RWH structure in India; the downstream spatial extent of artificial recharge from this RWH structure was similarly determined to be 600 m (Sukhija et al. 2005).

The average Cl$^-$ and δ^{18}O levels of the wells in the upper region of Jharapipla are bound by these three end-members and are interpreted to contain a mixture of them. A three end-member mixing model revealed the relative contribution of each end-member in the sampled wells (Table 2). In the first downstream well (JW1), 65% of the water present is determined to be artificially recharged water originating from the upstream *nadi*. Of the remaining 35% of the water in the well, 27% resembles the background groundwater (JW0), while 8% is similar to the enriched groundwater (JW3). Similarly, the second downstream well (JW2) is comprised of 39% *nadi* water, 46% background groundwater, and 15% enriched groundwater. Lastly, the fourth downstream well (JW4) is found to contain no artificially recharged groundwater. Instead, 91% of its water is similar to background groundwater, while 9% is comprised of enriched groundwater. This finding supports previous studies carried out in the neighboring State of Gujarat and the State of Andhra Pradesh, which conclude that similar RWH structures artificially recharge local groundwater in various geological settings of India (Sharda et al. 2006; Sukhija et al. 2005). Although the multi-end-member mixing model used in this study does not have a unique solution, the solution that best fits the conditions of the site has been presented.

Jharapipla: lower region

Similar to the upper region, the average δ^{18}O and Cl$^-$ values of the lower region of Jharapipla range from –5.30 to –2.91‰ and 40.59 to 143.71 mg/l, respectively, and reveal three distinct end-members (Table 1; Fig. 5): (1) harvested rainwater (JA) with low Cl$^-$ (40.59 mg/l) and

Table 2 Proportion of groundwater sources in each sampled well

Sample site	Artificial recharge	Natural recharge	
Jharapipla	(JN/JA)	(JW0/JW4)	(JW3)
JW0[a]	0%	100%	0%
JW1	65%	27%	8%
JW2	39%	46%	15%
JW3[a]	0%	0%	100%
JW4[a]	0%	91%	9%
JW5	26%	38%	36%
JW6	69%	7%	24%
JW7	75%	25%	0%
JW8	25%	4%	71%
Godawara	(GA*)	(GR)	(GBW)
GW0[a]	0%	37%	63%
GW1	35%	0%	65%
GW2[a]	0%	82%	18%
GW3	27%	66%	7%
GW4	59%	3%	38%
GBW[a]	0%	0%	100%
GW5[a]	4%	58%	38%

[a] Wells that are considered to not receive artificial recharge (<5% artificial recharge)

moderately elevated δ^{18}O (–3.29‰); (2) naturally recharged background groundwater (JW4) with moderate Cl$^-$ (92.51 mg/l) and very low δ^{18}O (–5.30‰); and (3) enriched groundwater (JW3) with high Cl$^-$ (183.32 mg/l) and relatively elevated δ^{18}O (–2.65‰). The water in JW4 is considered to be a distinct end–member for the lower region of the site, since it is very similar to the background groundwater upstream of the *nadi*. Furthermore, JW4 is assumed to be unaffected by artificial recharge from the *anicut* (JA), due to its upstream location.

Applying the three end–member mixing model to these data reveals the presence of artificially recharged water from the *anicut*, as well as naturally recharged local groundwater in the sampled wells of this region (Table 2). However, relative to the upper region of the site, the local groundwater with the enriched tracer signature (JW3) has a greater presence in the sampled wells (Figs. 4 and 5). The first well downstream of the *anicut* (JW5) contains 26% *anicut* water, 38% background groundwater, and 36% enriched groundwater. The second downstream well (JW6) has 69% *anicut* water, 7% background groundwater, and 24% of enriched water. Seventy-five percent of the water in the third downstream well (JW7) resembled *anicut* water, while the remaining 25% is comprised of background groundwater. The last downstream well (JW8) had 25% *anicut* water, 4% background groundwater, and 71% water similar to the enriched end-member.

The purpose of this analysis is to ascertain the relative fraction of artificially recharged groundwater in each well in the study area. However, spatial variation in naturally recharged groundwater is also noteworthy. Although it may be instinctive to only consider binary mixing between artificially recharged groundwater and naturally recharged groundwater, this study provides evidence that the complexity of the regional groundwater system can only be adequately explained using three-end member mixing. The adequacy of using the two most extreme natural recharge signatures as independent end-members is confirmed by the fact that all groundwater sampled in the study area falls within the two natural recharge end-members—background and enriched groundwater—and the RWH end-member.

Godawara

The average δ^{18}O and Cl$^-$ values for the sample sites at Godawara range from –4.89 to –0.17‰ and 1.70 to 253.21 mg/l, respectively, and reveal three distinct end-members (Table 1; Fig. 6). These end-members are (1) artificially recharged water from the *anicuts* (GA*) with moderate Cl$^-$ (84.48 mg/l) and elevated δ^{18}O (0.17‰); (2) local rainfall (GR) with very low Cl$^-$ (1.70 mg/l) and low δ^{18}O (–4.58‰); and (3) deep groundwater (GBW) with high Cl$^-$ (253.21 mg/l) and low δ^{18}O (–4.15‰). The groundwater from the remaining sampled wells fall within the bounds of these end-members and are considered to be a mixture of these waters.

Similar to Jharapipla, two of the three groundwater end-members present at the site represent natural recharge. The low Cl$^-$ and δ^{18}O signature of local rainfall reflects the rapid infiltration of naturally recharged shallow groundwater. The δ^{18}O values of rainfall collected in this study fell within the International Atomic Energy Agency (IAEA) recorded δ^{18}O values of precipitation for northwest India: –6‰ < δ^{18}O < –2‰ (IAEA 2001; Mukherjee et al. 2007). The low Cl$^-$ concentration in rainfall was similar to the weighted-average Cl$^-$ concentration of rainfall recorded in the neighboring State of Gujarat: 9.94 mg/l (Sharda et al. 2006). The low δ^{18}O composition and high Cl$^-$ concentration of the deep groundwater sample taken from a bore well indicates naturally recharged groundwater that has had more contact time with the sub-surface geology. Similar to rainfall, the δ^{18}O composition of this deep groundwater was also contained within the IAEA recorded δ^{18}O values of precipitation for northwest India (IAEA 2001), indicating that rapidly infiltrated rainwater is the ultimate source of deep groundwater in the unconfined aquifer present at Godawara. Although there was a clear groundwater sample that represented the less enriched naturally recharged end-member at the Jharapipla study site, the similarity between the δ^{18}O values of rainfall (–5.08‰) and this less enriched naturally recharged end-member (–5.36‰) provides additional support for the use of rainfall as the naturally recharged shallow groundwater end-member at Godawara (Table 1; Fig. 4).

While the rainfall and the deep groundwater end-members were easily recognized, determination of the most representative artificial recharge end-member required some interpretation. Due to evaporation, Cl$^-$ and δ^{18}O signatures of surface water are more seasonally variable than rainfall or groundwater (Price and Swart 2006). This trend is illustrated by the thick dashed line in Fig. 6, which represents a surface water evaporation line with respect to Cl$^-$ and δ^{18}O. The 'GA1–5/27/06' end of this evaporation line represents the

Cl⁻ and δ^{18}O values in the upper *anicut* at the end of the dry season after eight months of intense dry season evaporation. Conversely, the 'GR' end of the evaporation line represents rainfall, which is the initial signature of this impounded surface water prior to prolonged evaporation. The proximity of the lower *anicut*'s (GA2) Cl⁻ and δ^{18}O signature to the average rainfall signature (GR) confirms this. Unlike the upper *anicut* (GA1), the lower *anicut* was empty at the end of the dry season when this study commenced. Consequently, the water samples collected from the lower *anicut* during the study reflect recent monsoon rainfall that has had very little exposure to evaporation. This issue of seasonality in the RWH end-member is less notable in the Jharapipla study site, since the volume of surface water impounded behind the *nadi* is approximately 80 times larger than the upper *anicut* at Godawara. Consequently, we expected a considerably larger effect of evaporation on the tracer signatures of the RWH water at Godawara, due to a smaller volume of surface water.

The large error bars on the average Cl⁻ and δ^{18}O signature for the upper *anicut* (GA1) reflect the substantial variation of this tracer signature over the study period (Fig. 6). Since most of this study was carried out during the monsoon season, these average values are likely biased toward the rainfall end of the evaporation line. Therefore, it is likely that the annual weighted-average of Cl⁻ and δ^{18}O in the *anicut* lies closer to the dry season end of the evaporation line. A conservative estimate of the probable annual average of Cl⁻ and δ^{18}O in the *anicut* was determined by a best fit line for the wells that fell along the mixing line between the deep groundwater and the *anicut* end-members. The ultimate artificial recharge end-member (GA*) is reasonable because it falls near the midpoint of the surface water evaporation line and is the most expected end-member to explain the tracer signatures of the wells that are relatively enriched in Cl⁻ and δ^{18}O (GW1 and GW4).

The three end-member mixing model utilized for the average Cl⁻ and δ^{18}O data at this site suggests that three wells (GW1, GW3, and GW4) received a substantial proportion of artificial recharge from the RWH structures (Table 2). The percentages of artificial recharge determined in these wells over the study period were 35, 27, and 59%, respectively. The wells located directly downstream of the upper and lower *anicut*—GW1 and GW4, respectively, were estimated to have the greatest proportions of artificial recharge. Conversely, three wells (GW0, GW2, and GW5) were seen to be largely unaffected by current RWH activities. Only 4% of the water in the last downstream well (GW5) was shown to originate from the

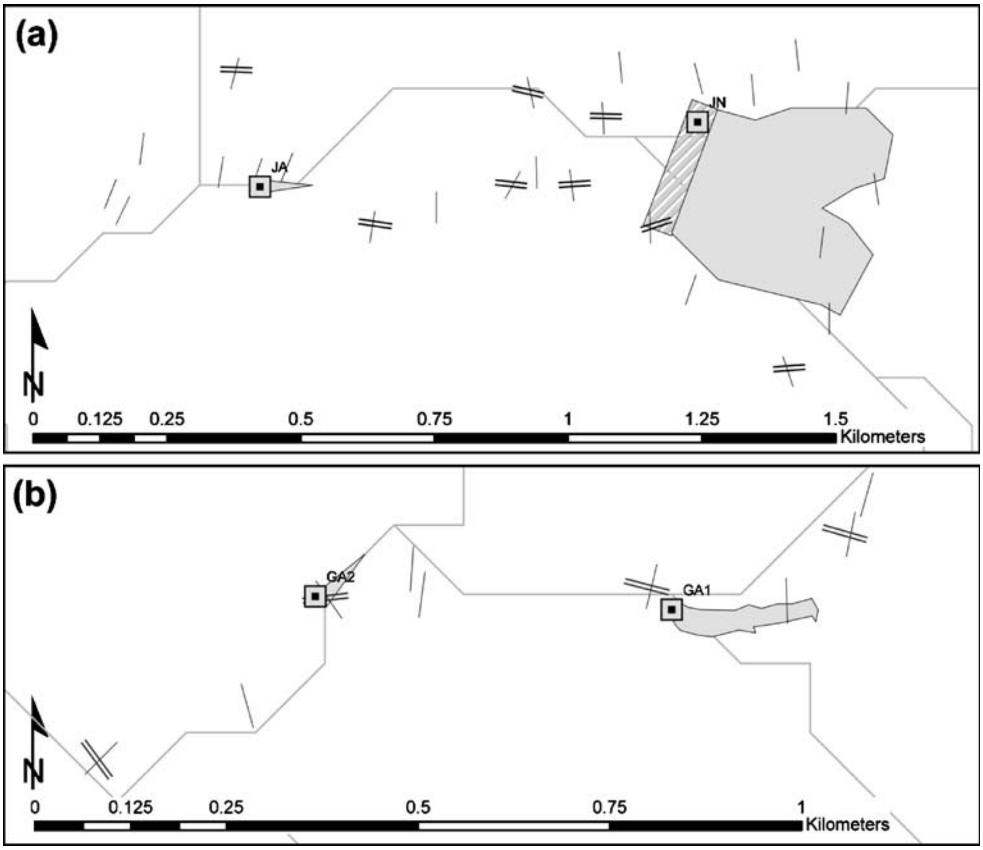

Fig. 7 Structural geology at the study sites: **a** Jharapipla and **b** Godawara. Cleavages are generally oriented perpendicular to streams (north–south), while joints are often parallel to streams (east–west). *Single lines* represent cleavages; *parallel double lines* represent joints; *double squares* signify RWH structures; polygons signify impounded surface water; *points* signify sampled wells; *light grey lines* signify streams

anicut, while the model indicates that none of the water in the well upstream of the upper *anicut* (GW0) or the second well located downstream of this *anicut* (GW2) were artificially recharged. Since the estimated proportion of artificial recharge in GW5 is less than 5%, this well is not considered to receive artificial recharge. Furthermore, the very low percentage of *anicut* water in this well suggests that the downstream spatial limit of artificial recharge from the lower *anicut* (GA2) is 390 m. This spatial extent is less than was observed with the *nadi* at Jharapipla and is considered to reflect the significant difference in size between these RWH structures (Stiefel 2007).

The use of groundwater tracers provides evidence that artificial recharge is present in many of the wells sampled within the proximity of the RWH structures at both study sites. The proportion of artificial recharge evident in these wells range from 25–75%. Similar artificial recharge proportions ranging from 52–83% were recorded in wells downstream of an Indian RWH structure situated in a similar hard rock terrain (Sukhija et al. 2005). Additionally, the use of $\delta^{18}O$ revealed that 50–70% of a groundwater system in Kenya was found to originate from analogous impounded surface water from a nearby lake (Ojiambo et al. 2001). However, our data also suggest that artificial recharge is not present in every well sampled. Spatial trends evident in the tracer data reveal that the wells located upstream of the RWH structures generally are not influenced by artificial recharge; this finding supports the regional downstream groundwater flow direction evident in the water table data and is evident in other RWH studies (Sukhija et al. 2005). Additionally, exceptions to the general spatial trend of decreasing artificial recharge in the downstream direction are also present within the study sites, suggesting that local groundwater flow paths are more complex and are sometimes counter to the regional trends.

Complex groundwater flow pathways

The results of this study disclose the nature of local groundwater-flow pathways present in the hard-rock aquifers of the study area. The tracer and groundwater level data provide evidence of complex groundwater flow pathways within the study sites. Complex groundwater-flow pathways are assumed when data suggest the presence of localized regions where groundwater does not follow the regional groundwater-flow direction. Support for complex groundwater flow was evident at the Jharapipla site in the enriched groundwater of JW3. Specifically, the groundwater in JW3 had relatively elevated levels of Cl^- and enriched $\delta^{18}O$ (Fig. 4), while the water level in this well was substantially higher than surrounding wells (Fig. 3). These factors suggest that this well was not directly hydrologically connected to many of the nearby wells. The non-linear distribution of artificial recharge in wells downstream of Jharapipla's *anicut* also suggests complex groundwater flow. These mixing estimates reveal that wells located relatively closer to the

Table 3 Effect of artificial recharge on the groundwater quality in wells

		Turbidity (NTU)	Sulfate (mg/l)	Fluoride (mg/l)	Electrical conductivity (μS/cm)	Total dissolved solids (mg/l)	Total hardness ($CaCO_3$) (mg/l)	Calcium hardness ($CaCO_3$) (mg/l)	Magnesium hardness ($CaCO_3$) (mg/l)	Alkalinity ($CaCO_3$) (mg/l)	pH
Receive Artificial Recharge	Mean	1.3	37.0	0.3	800	455.0	185.0	128.0	57.0	244.3	7.0
(JP.DW3, LY.DW1)	SE	0.2	11.0	0.1	27	29.9	9.0	5.9	4.4	7.9	0.2
No Artificial Recharge	Mean	5.3	55.3	0.8	867	466.7	251.3	158.7	92.7	236.2	7.0
(JP.UW1, GD.UW2, GD.DW2)	SE	0.8	14.0	0.3	87	39.2	28.1	16.0	12.9	30.9	0.2

SE standard error

source of artificial recharge did not always receive higher proportions of artificially recharged groundwater (Table 2). The irregular pattern observed in the water table within this lower region of the site provides additional evidence of complex groundwater movement (Fig. 3). A similar occurrence was evident at the Godawara study site in the water of GW2. Although this well was located downstream of the upper *anicut*, along the side of the streambed, the mixing model suggests it received no artificial recharge, while the next well further downstream (GW3) appears to have received water from the RWH structure (Table 2). The water-table surface was slightly depressed at the location of this well, suggesting that there may be sub-regions of groundwater that do not readily mix with surrounding groundwater (Fig. 3).

These abnormalities evident in the tracer data and water table are partially explained by characteristics of the hydrogeology of the study area. Since groundwater flow is restricted to the fractures present in the hard-rock aquifers, the structural geology of the study sites provides further insight into the movement of groundwater. The fractures in the study area are expressed as joints and cleavages. The overall orientation of the joints and cleavages are common at both sites: joints lie parallel to the streambeds (east–west), while the strike of the cleavages generally runs perpendicular to streambeds (north–south) (Fig. 7). Although cleavages are the dominant fracture feature (Chauhan et al. 1996), they are oriented perpendicular to the general direction of groundwater flow. As a result, groundwater utilizes the secondary fracture feature of the joints as a conduit for flow. The joints however, are relatively discontinuous compared to the cleavages. Therefore, groundwater is forced to flow along a complex pathway, utilizing both the joints and the cleavages, resembling a haphazard zigzag pattern. In a similar fractured hard-rock terrain in India, the majority of natural groundwater recharge occurred along preferential flow paths, mainly controlled by fractures (Sukhija et al. 2003). The data in our current study suggest that this preferential flow recharge process is applicable to artificially recharged water from the RWH structures, as well as natural recharge. Sukhija et al. (2006) mobilized Cl^-, $\delta^{18}O$, and radiocarbon dating in order to create a conceptual model to distinguish between different sources of groundwater based on various recharge paths for weathered-fractured hard-rock granites in central India. This study identified similar complex groundwater flowpaths to explain the variations in groundwater tracer data.

Impact of artificial recharge on the water quality in wells

Water-quality data reveal the impact of artificial recharge on the groundwater quality of the wells in the study area. A comparison of these data was made between wells found to receive artificial recharge and wells that were shown to contain no artificially recharged water (Table 3). These data were analyzed using descriptive statistics. The pattern that emerged from the mean data revealed a consistent difference between wells with and without artificially recharged water. The wells impacted by artificial recharge had lower levels of fluoride, sulfate, electrical conductivity (EC), total dissolved solids (TDS), calcium and magnesium hardness, and turbidity. High levels of these parameters are undesirable for human health and general domestic water use. The only exceptions to this trend were found in pH and alkalinity. There was no observed difference in pH levels, whereas alkalinity had a mean value that was slightly higher for wells receiving artificial recharge. However, this difference in alkalinity was relatively small (3%).

The increase in the alkalinity in artificially recharged water can increase by several mechanisms: an increase in pH; an addition of carbon dioxide; dissolution of carbonate minerals; addition of boron, silica, H_2S, or organic acids. Since the pH did not vary between wells receiving artificial recharge and those that did not, that is not a mechanism. Calcium and magnesium hardness

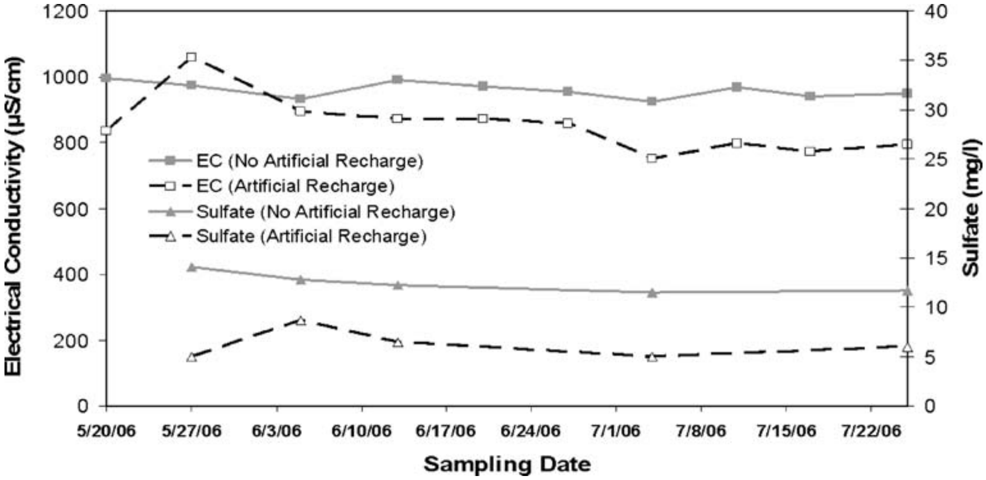

Fig. 8 Difference in water quality (EC and sulfate) between wells that were estimated to receive artificial recharge and wells that were not. The EC and sulfate concentrations were diluted in wells that received artificial recharge and therefore had improved water quality

values decreased in the artificially recharged wells; therefore, it cannot be the dissolution of carbonate minerals. Since carbon dioxide is expected to be higher in groundwater as compared to surface water, artificial recharge from surface water is not expected to cause an increase in CO_2. The addition of silica, H_2S, or organic acids is a possibility, especially since it is common for a deposit of sediments to be present at the bottom of RWH structures. Since the wells did not smell of hydrogen sulfide gas when sampling, the most likely additional source that would increase alkalinity would be organic acids from the sediments at the bottom of RWH structures. This conclusion is consistent with the nature of these RWH structures, since a layer of sediment often builds up over time due to the accumulation of eroded soil deposited from heavy monsoon rains.

Additional water quality data for sulfate and EC, which are known for each of the sampled wells over the entire study period, were used to confirm the trend in the initial water quality data (Fig. 8). Mean sulfate and EC values of the nine wells that were found to receive artificial recharge were 6.0 mg/l (standard error: SE = 0.5 mg/l) and 827 μS/cm (SE=32 μS/cm), respectively. The six wells shown to be unaffected by artificial recharge yielded 11.8 mg/l (SE= 1.0 mg/l) and 939 μS/cm (SE=28 μS/cm) as mean values of sulfate and EC, respectively. Therefore, the trend observed in the initial water quality dataset holds true for this larger dataset as well. Results from an analysis of variance (ANOVA) reveal that the presence of artificially recharged water in a well has a significant effect on the EC (p=0.00) and sulfate (p=0.00) levels in the well, based on a 95% confidence interval.

These data suggest that artificial recharge from the RWH structures affects groundwater quality through the dilution of natural levels of chemical constituents in groundwater. This finding is of consequence when applied to groundwater with elevated concentrations of fluoride and TDS. In many parts of Rajasthan, elevated fluoride levels in groundwater result in significant disease and health problems such as bone deformities and tooth decay (Ayoob and Gupta 2006). Additionally, the groundwater in many regions of the state is non-potable due to high levels of TDS (Sharma and Roy 2003). In both of these instances, artificial recharge through RWH efforts could reduce the concentrations of undesired constituents, improving the drinking water quality in wells that receive artificially recharged water (Kumar et al. 2005). This same principle may also help to reduce the concentration of arsenic in groundwater, which is a serious problem in many regions of India (Mukherjee et al. 2006). Although artificial recharge may not be the ultimate answer to eliminate these water-quality problems on a large scale, it may offer a partial solution.

Conclusions

This study provides a vital quantitative description of the impact of artificial recharge induced by RWH on the water supply and quality of wells in rural Rajasthan, India. Groundwater tracer tools, a geochemical mixing model, geological surveys, groundwater chemistry data, and groundwater level data were utilized to investigate the surface to groundwater interaction between RWH structures and adjacent wells. The use of $\delta^{18}O$ and Cl^{-} (mg/l) as geochemical tracers offers direct evidence of harvested rainwater in these wells, providing confirmation that RWH structures can increase reliable access to groundwater supplies. Results of this study indicate the presence of complex groundwater-flow pathways in the fractured hard-rock terrain of the study area and suggest that not all wells located in the nearby downstream vicinity of RWH structures will be influenced by artificial recharge. According to our results, water quality in wells that receive artificial recharge was improved through the dilution of chemical constituents in groundwater.

Further research is recommended to strengthen and extend these findings. It is reasonable to assume that there is an effect of seasonality present in the tracer data collected during this study. In order to improve this analysis, consistent tracer data collected over multiple years are necessary. Since the use of tracers shows great potential for future groundwater studies related to rainwater harvesting, it is recommended that future studies extend the length of the study period, utilize additional tracers to quantify rates of recharge and age of groundwater, e.g. $^{3}H/^{3}He$, and apply these tools to different sites in order to build a reliable dataset to guide future water-management planning in the basin.

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