Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region, Rajasthan, India

Bridget R. Scanlon · Abhijit Mukherjee · John Gates · Robert C. Reedy · Amarendra K. Sinha

Abstract Water and nutrient availability for crop production are critical issues in (semi)arid regions. Unsaturated-zone Cl tracer data and nutrient (NO_3 and PO_4) concentrations were used to quantify recharge rates using the Cl mass balance approach and nutrient availability in the Thar Desert, Rajasthan, India. Soil cores were collected in dune/interdune settings in the arid Thar Desert (near Jaisalmer) and in rain-fed (nonirrigated) and irrigated cropland in the semiarid desert margin (near Jaipur). Recharge rates were also simulated using unsaturated zone modeling. Recharge rates in sparsely vegetated dune/interdune settings in the Jaisalmer study area are 2.7–5.6 mm/year (2–3% of precipitation, 165 mm/year). In contrast, recharge rates in rain-fed agriculture in the Jaipur study area are 61–94 mm/year (10–16% of precipitation, 600 mm/year). Minimum recharge rates under current freshwater irrigated sites are 50–120 mm/year (8–20% of precipitation). Nitrate concentrations are low at most sites. Similarity in recharge rates based on SO_4 with those based on Cl is attributed to a meteoric origin of SO_4 and generally conservative chemical behavior in these sandy soils. Modeling results increased confidence in tracer-based recharge estimates. Recharge rates under rain-fed agriculture indicate that irrigation of 20–40% of cultivated land with 300 mm/year should be sustainable.

Keywords India · Groundwater recharge/water budget · Nutrients · Land use · Sustainability

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Introduction

Water scarcity is a critical issue in (semi)arid regions, which cover about one-third of the Earth's total land surface and host ~600 million people (Postel 1997). Water use and food production are strongly linked because irrigated agriculture is the primary consumer of global freshwater resources, accounting for ~90% of fresh groundwater consumption over the last century (Shiklomanov 2000; Scanlon et al. 2007a). India is particularly vulnerable to water and food scarcity because of its large population, ~1.1 billion, with a projected increase of an additional 570 million in the next 50 years; temporal variability in precipitation (~90% of precipitation in July, August, and September from the southwestern monsoon); and highest irrigated area by country globally—57 million hectares (Mha; UN-DESA-PD 2002; Kumar et al. 2005; Siebert et al. 2005). Groundwater-fed irrigated area has expanded from 30% (~7 Mha in 1960) to ~50% (~27 Mha in 1995; FAO 2008) and is likely to increase further as surface water supplies decrease after many of the glaciers have melted. The number of mechanized tube wells used for irrigation increased from 1 million in 1960 to ~19 million in 2000 (Deb Roy and Shah 2003). Current groundwater production rates are mining groundwater resources, particularly in western India, where groundwater levels are declining and over half of the irrigation wells are out of commission as a result of insufficient supply (Deb Roy and Shah 2003). In addition to impacts of limited water availability on crop production, some studies suggest that nutrient availability may be a primary constraint on crop yield in (semi)arid regions (Rockstrom and deRouw 1997).

Groundwater availability problems are likely to be exacerbated in the future by climate change. Average

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annual temperature is estimated to increase by 3.3°C in India by the end of the twenty-first century (Christensen et al. 2007), and irrigation water demand is estimated to increase by 10% per °C (Fischer et al. 2002). Winter precipitation is projected to decrease and summer precipitation to become more intense with fewer rainy days, further intensifying the hydrologic cycle and potentially reducing groundwater recharge (Christensen et al. 2007). Gross per capita water availability in India is estimated to decline from ~1,800 m^3/year in 2001 to ~1,100 m^3/year in 2050 (Gupta and Deshpande 2004). These water scarcity problems will most likely translate to food scarcity. A critical issue that needs to be addressed is how much water and nutrients are available for sustainable crop production.

Regarding agriculture and water resources, there is currently considerable emphasis upon sustainability of natural resource utilization. The Brundtlandt Commission (1987) defined sustainable development as "...development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Applying this concept to water resources suggests that water should only be consumed to the extent that it is renewable at human timescales. Some have criticized the use of recharge rates for assessing groundwater sustainability and argued that groundwater abstractions can be derived from increased recharge and decreased discharge, termed capture (Bredehoeft 2002; Devlin and Sophocleous 2005). However, in (semi)arid regions with generally deep water tables and very little surface water, pumpage is unlikely to capture surface flows. In these cases, recharge rates should, in the proper context, provide a good indication of the upper bound for sustainable groundwater abstraction rates. In addition to considering water quantity, sustainability should also address water quality issues, and development should try to minimize degradation of water resources.

Many studies have shown that subsurface flow through thick unsaturated zones can be approximated by piston-type flow (Cook and Herczeg 2000; Scanlon et al. 2007a). The concept of hydrostratigraphy can be applied to these flow systems to describe the resultant stratification or layering of pore water of different ages with depth. The subsurface distribution of environmental Cl tracer from bulk precipitation (precipitation and dry fallout) can be used to date the pore water and quantify past recharge rates (Allison and Hughes 1983; Scanlon et al. 2002). Chloride from bulk precipitation moves into the soil zone with infiltrating water. Drainage or percolation below the root zone is termed "potential recharge" and equated to eventual recharge at the water table. The age of unsaturated zone pore water is estimated by dividing the mass of Cl by the Cl input from bulk precipitation (wet and dry fallout). Chloride concentrations in soil water are inversely related to recharge rates: low Cl concentrations indicate high water recharge because Cl is flushed through the soil zone, whereas high Cl concentrations indicate low recharge because Cl is excluded when plants take up water and Cl builds up in the soil. Recharge is generally calculated using the chloride mass balance (CMB) approach (Allison and Hughes 1983). The hydrostratigraphic records trace past changes in recharge in response to variations in forcing from land-use change and climate variability (Scanlon et al. 2005, 2007a; Gates et al. 2008; Favreau et al. 2009). Unsaturated zone pore water NO_3 concentrations provide information on whether there is natural NO_3 in the profile from atmospheric deposition, as found in parts of the southwestern USA (Walvoord et al. 2003), from nitrogen fixation by native vegetation, as found in Senegal (Deans et al. 2005), or from mineralization and nitrification of soil organic nitrogen and over application and leaching of applied fertilizers in cropland areas (Scanlon et al. 2008). Large NO_3 reservoirs in unsaturated media or in groundwater can be considered a resource for crop production, minimizing the need for fertilizer application (Deans et al. 2005). Unsaturated zone soil cores and associated soil water Cl, NO_3, and PO_4 concentrations can be used to assess relationships between land use/land cover and climate, and subsurface water and nutrient cycles. These hydrostratigraphic records of water and nutrients are particularly valuable in remote (semi)arid regions where establishing and maintaining monitoring programs is extremely difficult.

In addition to use of the CMB approach to estimate recharge rates, numerical modeling is also widely used to estimate recharge rates in (semi)arid regions and to isolate controls such as climate forcing, vegetation, or soil type, on groundwater recharge. Fayer et al. (1996) used 1-D, unsaturated zone modeling to estimate recharge related to a variety of land use/land cover types in a semiarid region in northwest USA. Keese et al. (2005) used recharge modeling based solely on online data (precipitation, vegetation, and soils) to isolate controls on groundwater recharge and developed a map of recharge related to precipitation from 1-D simulations in different settings. Scanlon et al. (2003) simulated recharge over millennial time scales to compare with results from Cl tracer data in semiarid regions in the southwestern USA. The widespread availability of online data, including climatic forcing (Rodell et al. 2004), soil texture and related hydraulic databases, and vegetation data, greatly facilitates modeling analyses. Unsaturated zone modeling also provides a valuable tool to test the reliability of recharge estimates based on tracer data.

The objective of this study was to quantify recharge rates and nutrient reservoirs in the unsaturated zone for sustainable groundwater development and crop production in arid dune/interdune settings to the west in the Thar Desert and in semiarid cultivated settings along the margin of the desert to the east. Limited previous information on recharge in this region is based mostly on distribution of injected tritium in the unsaturated zone, which provides recharge estimates in natural grassland settings for the monsoon period after tracer injection (Rangarajan and Athavale 2000). The current study differs from previous studies in that it provides long-term (decadal) average recharge rates. The study areas should also provide information on controls on groundwater recharge because climate in the study areas ranges from arid to semiarid and land use ranges from natural, sparsely vegetated dunes to nonirrigated (rain-fed) and irrigated cropland. Information on subsurface water availability and nutrient levels in the cultivated region to the east will be valuable for assessing sustainability of crop production in this area.

Background

Study area characteristics and history

The Thar Desert, also known as the Great Indian Desert, is the seventh-largest desert in the world. It covers northwest India, mostly in the state of Rajasthan (340,000 km^2 area) and southeast Pakistan. There is generally no integrated surface drainage system to the nearest ocean; surface water drains to varying-sized depressions or playas, which evaporate and often contain alkaline brine. Because of scarcity of surface water resources, inhabitants depend mostly on groundwater. Groundwater development is much more intensive in the eastern semiarid areas than in the western arid parts because of land use and population growth.

Western study area

The western study area is within a ~50-km radius of the city of Jaisalmer in the district of Jaisalmer, with an average elevation of 150–200 m above mean sea level (Fig. 1). Geomorphology consists mostly of extensive ancient and modern dune fields and interdune plains (Fig. 2a,b). The modern dunes (5–40 m high), which are mostly transverse (Barchan) type dunes, are oriented NE–SW and are composed of medium to fine sand. Interdune plains consist of coarse sand overlying weathered bedrock. The climate is arid to extremely arid (UNEP 1991). Mean annual precipitation (MAP) is 178 ± 92 (1 standard deviation, SD) mm (Fatehgarh, 1929–1967 omitting 1951–1953 because of minimal data) and 155±67 mm (Nachna, 1930–1966 omitting 1950–1953 and 1966) (Source: Global Historic Climatic Network, GHCN, Vose et al. 1998). Most precipitation (77–78%) occurs during the summer monsoon in July and August (Fig. 3). Average temperature in Jaisalmer ranges from 7.9°C (January) to 41.6°C (May) (SRSA 1999). Potential evapotranspiration (PET) (1,800 to >2,000 mm/year; SRSA 1999) generally exceeds annual precipitation, even during the monsoon season. Groundwater exists mostly in Mesozoic to Tertiary sandstone and limestone aquifers (Sahai et al. 1993; SRSA 1999). Unsaturated zone thickness varies from 100 to 150 m in dune fields and generally ≤60 m in interdunes.

Because of scarcity of precipitation and groundwater, cultivation is limited to rain-fed agriculture in a few interdune plains. The crops, mostly pearl millet, barley, and fodder, depend on monsoonal rainfall and are generally grown once every 2–3 years, depending on precipitation. An irrigation canal (30 m wide) was constructed in the northwestern part of the study area (Indira Gandhi Canal Project) to supply water from tributaries of the Indus River to highly water scarce villages in the area (Fig. 1). Plantations have been developed in certain regions along the canal to provide windbreaks and reduce sand migration into the canal (Fig. 2c; Jain et al. 2007).

Eastern study area

The eastern study area is north and west of the city of Jaipur (capital of Rajasthan state), in the district of Jaipur

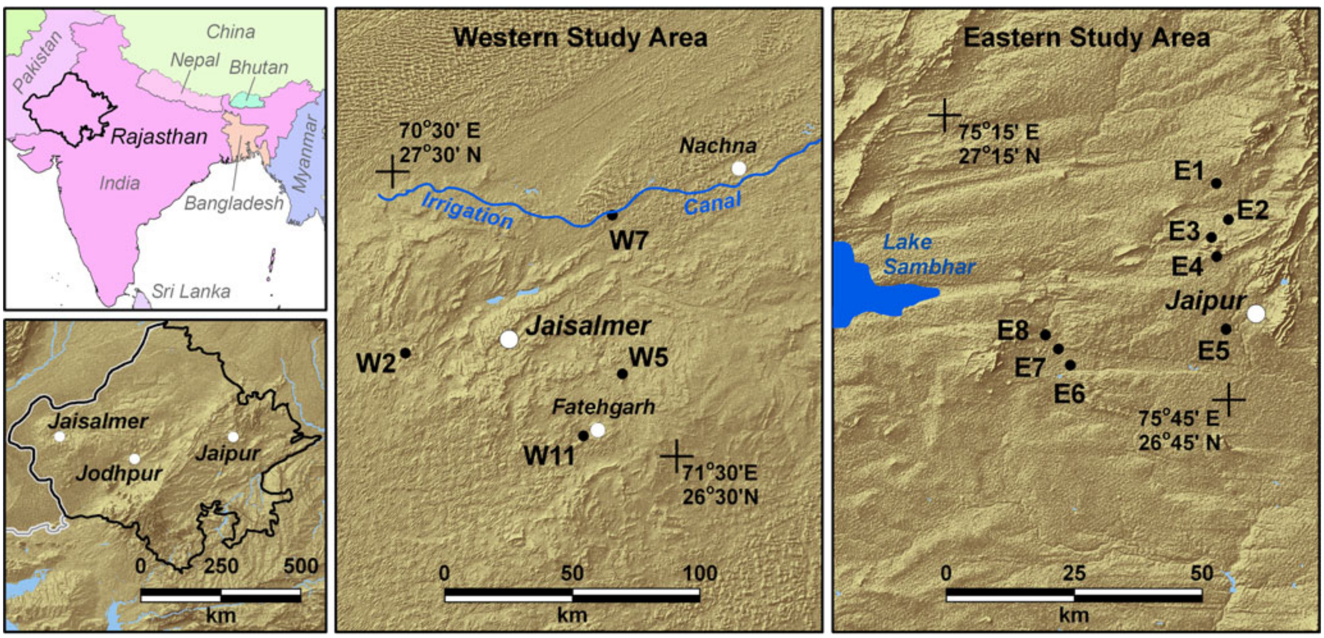

Fig. 1 Shaded relief maps showing western (near *Jaisalmer*) and eastern (near *Jaipur*) study areas in Rajasthan, India. Towns/cities shown with *white symbols*, and borehole locations shown with *black symbols*. Borehole settings: *W2* and *W5*, dune; *W11*, interdune; *W7*, interdune plantation; *E2* and *E3*, rain-fed; *E1*, *E4*, and *E5*, fresh groundwater irrigated; *E6*, *E7*, and *E8*, brackish groundwater irrigated. *Insets* show locations of Rajasthan in India and of referenced towns/cities in Rajasthan

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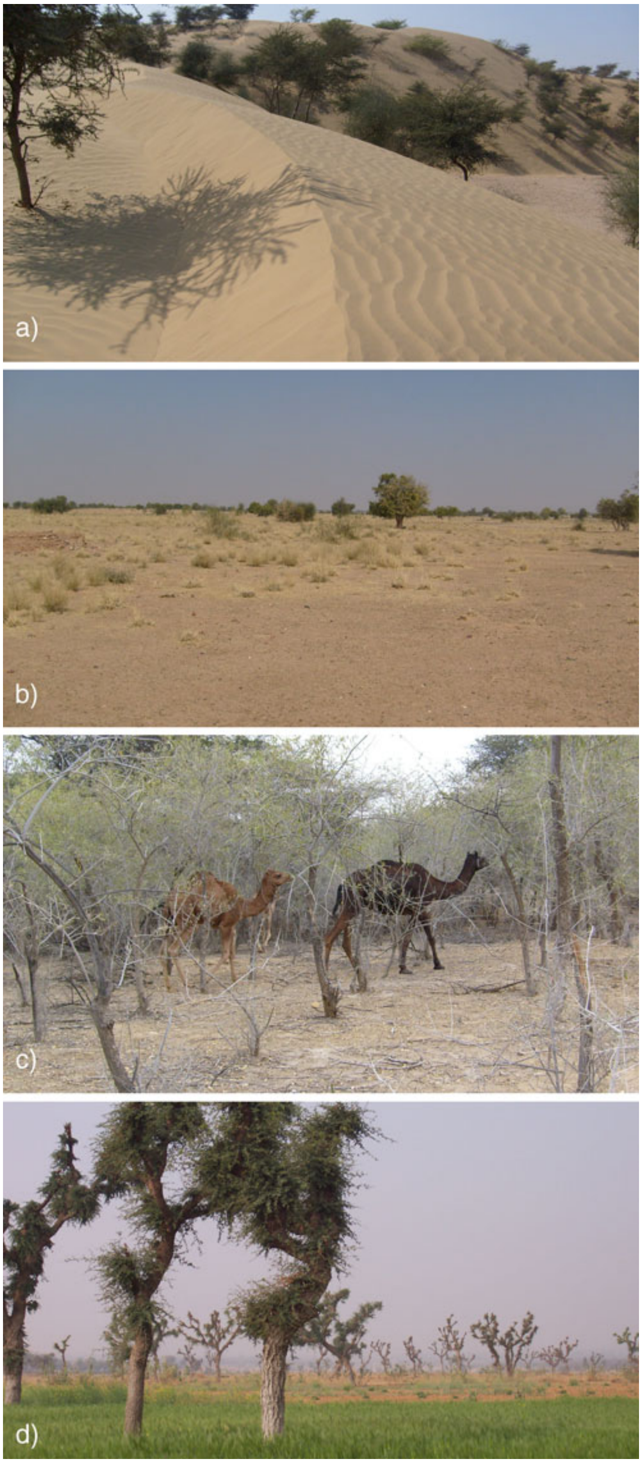

Fig. 2 Photographs of borehole sites, **a** W5, modern dune, **b** W11, interdune, **c** W7, interdune plantation, and **d** E8, high-salinity groundwater irrigation

(Fig. 1). Surface sediments consist of Quaternary-age loess sediments and residual sand dunes (Wasson et al. 1983; SRSA 1999). Most small streams in the area, which originate in the northeast, drain toward the west to a large saline playa lake (Lake Sambhar). The moderately thick unsaturated zone in the area consists of mostly sand and silt, with occasional calcrete. Water-table depths generally range from 20 to 40 m (SRSA 1999). The aquifers consist of unconsolidated Quaternary sediments and underlying metasediments. Recent groundwater development in the area has led to overdraft and rapid water-table declines of 3–7 m between 1984 and 1997 (SRSA 1999). However, in some localities, such as near Lake Sambhar and near the city of Jaipur, the water table fell as much as 12 m in the 1990s (SRSA 1999).

The climate is semiarid (UNEP 1991), with mean annual precipitation of 604±229 mm/year at Jaipur meteorological station (1868–2000 omitting 1870, 1873, 1969, 1973, 1976–1978, 1981; source: GHCN, Vose et al. 1998). Most (66%) precipitation occurs during July and August (Fig. 3). In Jaipur, mean temperature ranges from 8.3°C (January) to 40.6°C (May), and PET ranges from 1,700 to 1,800 mm/year.

Natural vegetation in the study area consisted of shrubs and grasses. Much of the area has been cultivated since prehistoric times and includes nonirrigated (rain-fed) and irrigated cropland (Fig. 2d). Because nomadic tribes and settlers have inhabited this area for thousands of years (Sharma 1966), it is very difficult or impossible to identify any region that has not been cultivated previously. Currently irrigated sites have had periods of rain-fed agriculture in the past. Whereas irrigated areas yield two to three different crops during a year, rain-fed crops are produced only during the monsoon season. Crops are mostly wheat, pearl millet, barley, and malt.

Precipitation chemistry

Monitoring stations for precipitation chemistry are limited and are maintained by the Indian Background Air Pollution Monitoring Network (BAPMoN). The most comprehensive long-term (1976–1987) published measurements of wet-only deposition are available for the station in Jodhpur (26°18′N, 73°01′E), midway between the two study areas (~300 km from Jaipur and Jaisalmer; Mukhopadhyay et al.

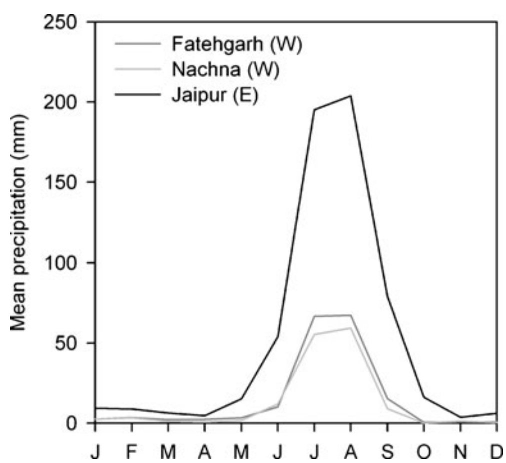

Fig. 3 Mean monthly precipitation measured at two locations near the western (*W*) study area (*Fatehgarh* and *Nachna*) and at the eastern (*E*) study area (*Jaipur*) based on data from 1929 to 1967 (Fatehgarh), 1930 to 1966 (Nachna), and 1868 to 2000 (Jaipur)

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1992). Volume-weighted mean annual Cl concentration in precipitation is 2.0±0.62 mg/L. Calculations for the CMB require information on Cl input from precipitation and dry fallout (bulk precipitation); however, no data are available to suggest how to modify wet-only precipitation input for dry deposition. The value of 2 mg/L was, therefore, used for CMB calculations as a lower bound. Mean precipitation at Jodphur for 1976–1987 (380 mm) is also between precipitation values at both study sites (165 mm, Jaisalmer, and 600 mm, Jaipur); however, the Cl deposition was not modified by precipitation amount because of insufficient information. BAPMon data also include information on SO_4 in precipitation (1.9±1.8 mg/L; Mukhopadhyay et al. 1992).

Methods

Field methods

Boreholes were drilled in January and February and sediment samples collected in the western study area near Jaisalmer in 2007 and in the eastern study area near Jaipur in 2008 (Fig. 1, Table 1). The western study area includes two boreholes in dunes, one in an interdune setting and one in an interdune setting with a plantation adjacent to an irrigation canal (Fig. 1). Three additional boreholes were drilled in interdune settings but were not sufficiently deep (1.2–2.4 m) because of shallow bedrock to provide useful information for the study's objectives. The eastern study area includes three boreholes in currently rain-fed sites and five in currently irrigated sites. Borehole depths range from 3.0 to 14.6 m, with deeper boreholes mostly in the eastern site.

In the western study area, sediment samples were obtained using a hollow-stem hand auger with interchangeable 1.5-m aluminum rods and 70-mm-diameter opening (Dormer Engineering, Australia). In the eastern study area, a mechanized hollow-stem rotary drill rig with a 150-mm-diameter opening, generally used for tube-well installation, was used to collect sediment samples. From each of the drilling sites, past and present land-use data, water-table depth, and other relevant information were collected from local sources.

Bulk sediment samples of ~200 g were collected at ~0.15-m-depth intervals for the top 1.5-m, 0.3-m intervals for 1.5–4.6 m, 0.9-m intervals for 4.6–11 m, and 1.8-m intervals to maximum borehole depth. Samples were immediately placed in air-tight plastic cups, sealed with parafilm or plastic tape, and then sealed in air-tight polyethylene bags to minimize sample drying. Groundwater samples were collected from three irrigated sites in the eastern study area. Groundwater samples were stored in 125-ml HDPE bottles without any preservative. Sediment and groundwater samples were shipped to The University of Texas at Austin for analyses.

Laboratory methods

Water-extractable concentrations of anions (Cl, SO_4, NO_3, and PO_4) were analyzed in water leached from 211 unsaturated zone sediment samples. About 40 ml of double deionized water was added to ~25 g of soil in centrifuge tubes. The mixture was placed in a reciprocal shaker for 4 h and then centrifuged at 7,000 rpm for 45 min to separate water from sediment. The supernatant was filtered (0.2 µm) and stored at 4°C before being analyzed by ion chromatography (Dionex ICS2000). Residual sediments in the centrifuge tubes were then oven dried at 105°C for 48 h to determine gravimetric water content. Water-extractable ion concentrations are expressed on a mass basis as mg of ion per kg of dry soil—supernatant concentration × extraction ratio (g water/g soil) and divided by water density. Ion concentrations are also expressed as mg of ion per liter of

Table 1 Borehole concentration and inventory values for chloride, sulfate, nitrate (*N*), and phosphate (*P*). Concentration values represent depth-weighted means, and inventory values are normalized by indicated depth interval. *W2*, *W5*: dunes; *W11*: interdune; *W7*: interdune plantation

Setting borehole	Depth (m)	WC (g/g)	Mean concentration (mg/kg, ≥1 m depth)				Mean concentration (mg/L, ≥1 m depth)				Normalized inventory (kg/ha/m, ≥1 m depth)				Normalized inventory (kg/ha/m, ≤1 m depth)			
			Cl	SO_4	N	P	Cl	SO_4	N	P	Cl	SO_4	N	P	Cl	SO_4	N	P
Jaisalmer																		
W2	4.6	0.01	1.0	1.9	0.15	0.07	–	–	–	–	16	31	2.4	1.2	13	31	5.5	1.6
W5	11.0	0.00	0.6	1.2	0.42	0.11	–	–	–	–	10	19	6.7	1.7	17	38	20	1.9
W11	3.0	0.01	1.6	2.1	<0.01	<0.01	–	–	–	–	25	33	<0.24	<0.24	28	58	5.4	0.43
W7	4.6	0.02	30	23	0.85	0.07	–	–	–	–	480	370	14	1.2	64	66	28	2.1
Jaipur, rain-fed																		
E2	10.0	0.05	1.5	2.0	0.05	0.11	29	58	1.4	2.6	25	32	0.85	1.7	48	36	12	2.2
E3	6.3	0.05	0.6	1.0	0.04	0.88	13	20	0.7	16	10	15	0.57	14.0	26	21	23	36
Jaipur, irrigated (fresh groundwater)																		
E5	12.7	0.06	4.1	4.4	2.7	0.12	86	90	57	3.5	66	70	43	2.0	95	61	60	20
E1	11.0	0.09	6.3	2.8	1.6	0.10	68	33	17	1.0	100	44	25	1.5	47	24	64	38
E4	13.2	0.11	7.8	4.8	1.2	0.07	66	42	9.5	0.78	120	77	19	1.1	170	100	160	7.9
Jaipur, irrigated (brackish groundwater)																		
E6	6.0	0.05	210	58	0.34	0.05	3,900	1,100	6.2	1.1	3,100	860	5.8	0.71	1,500	560	49	3.8
E7	14.6	0.06	18	6.5	0.34	0.03	280	110	5.5	0.55	290	100	5.4	0.55	190	110	98	3.0
E8	14.6	0.06	63	9.5	0.27	0.02	970	190	3.7	0.40	3,100	470	13	1.1	4,400	590	170	3.7

WC water content; *N* NO_3–N; *P* PO_4–P

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pore water by dividing mg/kg by gravimetric water content and multiplying by water density. Because of potential water loss during sample collection and processing, ionic concentrations on a mass basis (mg ion/kg dry soil) are considered more reliable than concentrations expressed on a pore water volume basis (mg ion/L soil water). Water loss during sample collection or processing would result in overestimation of ionic concentrations as mg/L. Salt inventories (kg/ha) were calculated by multiplying depth-weighted salt concentrations (mg/kg) by interval thickness (m), soil bulk density (kg/m^3), and a unit conversion factor of 10^4 (m^2/ha).

Data analyses

Previous studies have estimated drainage or percolation rates below the root zone or recharge to groundwater using the CMB method (Allison and Hughes 1983). According to the CMB method in natural systems and rain-fed agricultural systems, percolation (Pe) or recharge (R) rates are calculated as follows:

$$P \times Cl_p = Pe \times Cl_{uz} \ or \ R \times Cl_{uz}, \qquad Pe = R = \frac{P \times Cl_p}{Cl_{uz}} \tag{1}$$

where P is precipitation, Cl_p is Cl concentration in bulk precipitation (wet and dry fallout), and Cl_{uz} is Cl concentration in unsaturated zone pore water. The CMB approach requires unsaturated zone Cl concentrations in mass/volume, usually reported in mg/L. If samples undergo drying during collection or processing, Cl_{uz} may be overestimated, and calculated recharge rates would be underestimated. If Cl is added to the system in irrigation water, then irrigation rate (I, mm/year) and Cl concentration in irrigation water (Cl_I) need to be included as follows:

$$Pe = R = \frac{P \times Cl_p + I \times Cl_I}{Cl_{uz}} \tag{2}$$

Water fluxes were calculated for each depth interval, and depth-weighted averages were calculated over prespecified depth intervals. There are a number of assumptions required to apply the CMB approach, including one-dimensional (1-D), vertical downward, piston-type flow, and no subsurface sources or sinks for Cl. The geochemically conservative behavior of Cl and the high solubility of halite result in Cl being widely used for recharge calculations.

Mass balance calculations can be applied to other tracers to estimate recharge if the tracer input can be quantified and the tracer behaves conservatively, i.e., no subsurface sources or sinks. Sulfate has not previously been used to estimate recharge because there are other sources of SO_4, such as gypsum dissolution, and SO_4 can sorb onto sediments (Scanlon et al. 2009). If SO_4 input from precipitation is known and there are no subsurface sources or sinks for SO_4, a similar mass balance expression can be written for estimating percolation or recharge rates:

$$P \times SO_{4p} + I \times SO_{4I} = Pe \times SO_{4uz} \ or \ R \times SO_{4uz}, \qquad Pe = R = \frac{P \times SO_{4p} + I \times SO_{4I}}{SO_{4uz}} \tag{3}$$

Comparison of percolation/recharge rates from SO_4 with those based on Cl provides the best test of whether SO_4 can be used to estimate percolation/recharge. Uncertainties in Cl and SO_4 inputs (precipitation or salt concentrations in precipitation) would be linearly translated into uncertainties in recharge rates because the equations are linear. The time (t, year) required to accumulate Cl or SO_4 in the subsurface was estimated by dividing the cumulative mass of Cl or SO_4 in the profile by Cl or SO_4 input:

$$t = \frac{\sum Cl_{uz}\rho_b dz}{PCl_P + ICl_I} = \frac{\sum SO_{4uz}\rho_b dz}{PSO_{4P} + ISO_{4I}} \tag{4}$$

where subscripts *uz*, *P*, *and I* refer to concentrations of Cl or SO_4 in unsaturated zone pore water (mg/kg), in bulk precipitation (wet and dry fallout; mg/L), and in irrigation water (mg/L), respectively, ρ_b is soil dry bulk density (kg/m^3), dz is depth interval, P is precipitation (mm/year), and I is irrigation rate (mm/year). In natural and rain-fed cropland systems, the only Cl or SO_4 input is from bulk precipitation. It is sometimes difficult to determine inputs in irrigated profiles. Omission of an input, such as irrigation, in irrigated profiles would result in overestimation of accumulation time.

Numerical modeling

To provide an independent comparison with CMB-based recharge estimates, water flux through the unsaturated zone was simulated using the Hydrus 1-D water flow model (Simunek et al. 2005), combined with atmospheric forcing boundary conditions from land surface model outputs and literature-based parameter values. This approach is suitable for testing whether CMB calculations are consistent with available climate, vegetation, and soil information; however, considering the paucity of site-specific field parameters or calibration data, modeled percolation or recharge rates should be viewed as preliminary estimates only. Model geometry consisted of a 1-D 3-m-deep profile discretized into 30-mm intervals. Initial conditions were based on measured water content of 0.02 m^3/m^3 in the western study area and 0.05 m^3/m^3 in the eastern study area. Typical soil water retention parameters for clean sand (van Genuchten parameters: saturated water content, 0.43 m^3/m^3; residual water content, 0.02 m^3/m^3; α, 0.145/cm; n, 2.68; and saturated hydraulic conductivity, 7.13 m/day; Carsel and Parrish 1988) were used to describe hydraulic properties of the sediment. Upper boundary conditions were provided by

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reference evapotranspiration (ET_{ref}) and precipitation (P) outputs from the Global Land Data Assimilation System (GLDAS) at 3-h intervals from 24 February 2000, through 2007 (Rodell et al. 2004). Leaf area index for partitioning ET_{ref} into potential evaporation and potential transpiration was estimated from the literature (White et al. 2000; Asner et al. 2003). Root-water uptake was assumed to decrease exponentially with depth (Zeng 2001). Parameters for determining reduction of root-water uptake due to water stress were chosen to be consistent with xylem cavitation ranges for xeric vegetation—anaerobiosis potential: 0.0 to −0.3 m; optimal potential, −0.3 to −10 m; wilting point, −500 m (western site) and −150 m (eastern site; Feddes et al. 1978; Pockman and Sperry 2000). Percolation below 3 m was considered representative of potential recharge and used to calculate an average annual recharge rate.

Results and discussion

Although the number of boreholes drilled in each study area is limited and the range in climate and land-use conditions varies widely between western and eastern study areas, some general trends emerge. A plot of SO_4 inventories versus Cl inventories below the root zone (1 m depth) shows a grouping of profiles in the various settings (Fig. 4). Although SO_4 may often be derived from dissolution of gypsum and other minerals, SO_4 in these study areas seems to be derived primarily from precipitation and irrigation inputs. Profiles in dune/interdune settings in the western study area generally have low SO_4 and Cl inventories, with the exception of the profile beneath the plantation, which has higher inventories. Cultivated sites in the eastern study area beneath rain-fed cropland have inventories similar to those in dune/interdune settings in the western study area because precipitation provides the only salt input to the system. Profiles beneath sites that were irrigated at some time in the eastern study area have higher SO_4 and Cl inventories, particularly profiles that have been irrigated with brackish groundwater.

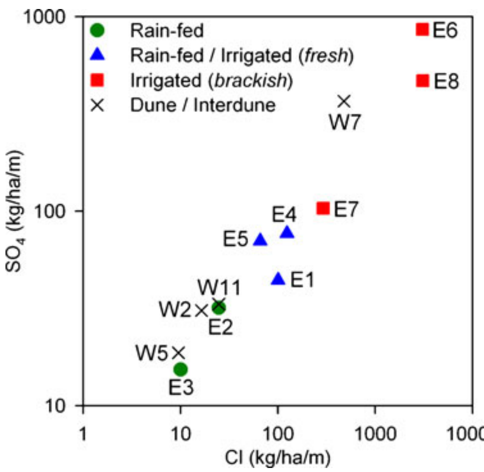

Fig. 4 Relationship between chloride and sulfate inventories normalized by depth for dune/interdune settings in the western study area and rain-fed and irrigated sites in the eastern study area

Recharge rates and salt and nutrient inventories in the western study area profiles

Profiles in the western study area near Jaisalmer are sandy (mean sand content 94–99%; Table 2). Dune profiles (W2 and W5) are characterized by extremely low water contents, with mean values for profiles of 0.00–0.01 g/g below 1 m depth (Fig. 5, Table 1). Although these low water contents may be natural, the extremely low values suggest that they may have been impacted by sample drying during collection or processing because of the extreme sandy nature of the sediments (W5, 99% sand). Mean Cl concentrations and inventories ≥1 m depth are low (0.6 and 1.0 mg/kg; 10 and 16 kg/ha/m) in dune settings (Fig. 5, Table 1). Concentrations of Cl are low throughout the profiles (0.3–3.7 mg/kg), with no well-defined peaks (Fig. 5). The low water contents would result in overestimation of Cl concentrations in mg/L if they were an artifact of sample drying. Dunes are sparsely vegetated (Fig. 2a), and the time required to accumulate Cl in dune profiles is 18 and 34 years (Table 3). Dune/interdune areas have large topographic relief (~35 m), which makes it difficult to apply the CMB 1-D analysis to subsurface recharge calculations. However, the uniformly low Cl concentrations indicate depth-weighted mean recharge rates ≥1 m below surface of 2.7 and 3.2 mm/year, representing 2% of long-term precipitation (Table 3). These recharge rates provide a lower bound on actual recharge rates if sediment samples were affected by drying. Inventories and concentrations of SO_4 are also low throughout the profiles, indicating that SO_4 is likely of meteoric origin (Fig. 5, Table 1). Concentrations of SO_4 were also used to estimate recharge rates using a mass balance approach (Eq. 3), similar to that for Cl. Calculated recharge rates based on SO_4 (1.3 and 1.4 mm/year) are slightly lower than those based on Cl (Table 3).

The interdune profile (W11; 3 m deep) is shallower than the dune profiles (4.6 and 11 m). Depths of interdune profiles were restricted because of bedrock. Soil texture, water contents, and Cl concentrations in the interdune profile are similar to those in dune profiles (Fig. 5, Tables 1 and 2). Chloride accumulation time to the base of the profile (3 m depth) is 23 years, similar to values for dune profiles. Estimated recharge rate is 5.6 mm/year (3% of precipitation), slightly higher than those estimated for dunes (Table 3).

Concentrations and inventories of NO_3 and PO_4 within and below the top meter are all low in both dune and interdune settings, indicating low nutrient levels in these sandy soils and lack of N fixation by sparse vegetation or mineralization of soil organic nitrogen (Fig. 5, Table 1). The nutrient inventory is slightly higher in the upper meter of the interdune setting.

Profile W7 is also in an interdune setting where a plantation was developed adjacent to an irrigation canal (Fig. 2c). The plantation was established ~30 years ago to minimize transport of sand into the canal. This profile differs from other dune and interdune profiles in having higher Cl concentrations (mean 30 mg/kg) and inventories (480 kg/ha/m; Fig. 5, Table 1). The profile extends only to a depth of 4.6 m, and the peak Cl concentration (49 mg/kg) is at 2.1 m depth. A high correlation between Cl and

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Table 2 Depth-weighted mean sand, silt, and clay for measured profiles

Borehole	Sand (%)	Silt (%)	Clay (%)
W5	99	0	1
W11	94	4	2
W7	95	3	2
E2	83	10	7
E3	94	3	3
E1	84	10	6
E6	72	19	9
E7	71	19	10

SO_4 (r=0.95) suggests a common source. Increased water uptake by trees would increase Cl concentrations in mg/L but should not affect the Cl mass concentration (mg/kg). High Cl and SO_4 mass concentrations, therefore, indicate that the site was probably irrigated to establish the plantation, although there is currently no evidence of irrigation. Concentrations and inventories of NO_3 and PO_4 are a little higher in this profile than other profiles in this study area and may reflect inputs from irrigation water (Table 1).

Modeling of recharge in the western study area

Unsaturated zone water fluxes were simulated in sandy soils to represent water movement in sandy dune sites. The simulation period is from 24 February 2000 through 2007, which is the period for which GLDAS forcing is available (Rodell et al. 2004). Mean annual precipitation (MAP) for the simulation period (131 mm) is similar to long-term MAP (155–178 mm/year; ~1930 to mid-1960s); therefore, this precipitation record should be representative of long-term conditions. A mean recharge rate of 22 mm/year was simulated for nonvegetated conditions, which provides an upper bound on recharge that results from climatic forcing. Sparse vegetation was approximated by a maximum leaf area index of 1, and sensitivity analyses were conducted to assess impacts of varying rooting depth. Simulated rooting depths were 0.5, 1.0, 1.5, and 2.0 m, and resultant recharge rates were 17, 4.6, 0.9, and 0.0 mm/year, respectively. Mean recharge rates resulted from averaging over the 7-year simulation period; however, recharge occurred only in 2007. The CMB-based recharge estimates of 3–6 mm/year are generally consistent with simulated

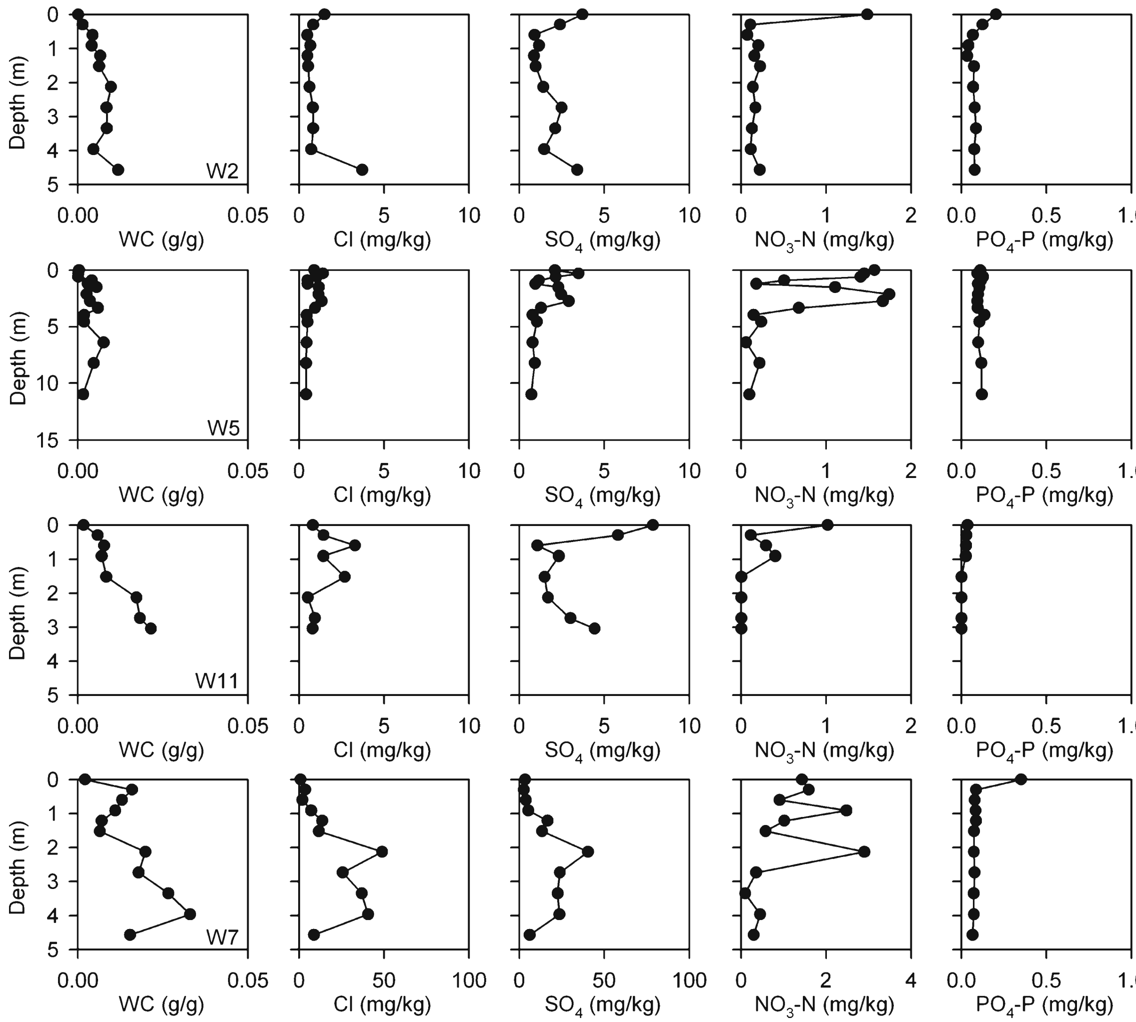

Fig. 5 Representative water content (*WC*), chloride, sulfate, nitrate (*N*), and phosphate (*P*) profiles for boreholes located in the western study area: *W2* and *W5*, dune; *W11*, interdune; and *W7*, interdune plantation. Concentrations in mg/L are not shown because measured water contents may not be reliable. For location of boreholes, see Fig. 1, and for photos of selected borehole locations, see Fig. 2

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Table 3 Chloride accumulation times (*CMB age*) based on entire profile, chloride mass balance (*CMB*) and sulfate mass balance (*SMB*) annual recharge flux, and corresponding percentage of mean annual precipitation (*P*) for borehole profiles in the western (W) and eastern (E) study areas based on concentrations below 1 m depth except as noted

Borehole	Land use	CMB age (years)	CMB flux		SMB flux	
			(mm/year)	% of *P*	(mm/year)	% of *P*
W2	Dune	18	3.2	1.9	1.4	0.85
W5	Dune	34	2.7	1.6	1.3	0.79
W11	Interdune	23	5.6	3.4	2.2	1.3
E2	Rain-fed	23	61	10	44	7.3
E3	Rain-fed	6.7	94	16	72	12
E5[a]	Rain-fed	8.0	120	20	17	2.8
E8[b]	Rain-fed	28	50	8.3	47	7.8
Irrigated with fresh groundwater						
E5	Irrigated	72	98	16	39	6.5
E1	Irrigated	87	28	4.6	47	7.8
E4	Irrigated	140	18	3.0	28	4.7
Irrigated with brackish groundwater						
E6	Irrigated	7,100	0.3	0.05	1.5	0.25
E7	Irrigated	350	5.6	0.93	15	2.5
E8	Irrigated	1,500	33	5.5	43	7.2

Values are calculated using mean annual precipitation of 165 mm/year for the western study area and 600 mm/year for the eastern study area, with 2.0 mg/L Cl and 1.9 mg/L SO_4 concentrations in precipitation for both study areas and assuming no irrigation inputs. Recharge rates for all irrigated profiles represent minimum values because irrigation input is omitted from the CMB and SMB calculations.

[a] Depth intervals representing rain-fed agriculture of currently irrigated profiles below 8.2 m depth

[b] Depth intervals representing rain-fed agriculture of currently irrigated profiles 6.4–13.7 m depth interval

recharge for the root-zone depth of ~1 m. There are many limitations to this modeling exercise, including lack of site-specific data and short boundary condition time series. However, simulation results suggest that CMB recharge estimates should be reasonable.

Recharge rates and salt and nutrient inventories in the eastern study area

All sites sampled in the eastern study area near Jaipur are cultivated. Inventories of Cl and SO_4 generally fall into three groups: lowest inventories under rain-fed cropland, moderate inventories under mixed rain-fed/irrigated cropland in an area of fresh groundwater, and highest inventories under rain-fed/irrigated cropland in an area of brackish groundwater (Fig. 4, Table 1). Measured Cl and SO_4 concentrations in groundwater samples in the area of fresh groundwater are low (Cl: 37 and 66 mg/L; SO_4: 5.6 and 30 mg/L), whereas concentrations were much higher in the area of brackish groundwater (Cl: 850 and SO_4: 170 mg/L). Elevated salinity in profiles in the area of brackish groundwater is attributed to proximity (≤10 km distant) to Lake Sambhar with its associated evaporite deposits and not to irrigation return flow.

Profiles under rain-fed cropland (E2 and E3) are generally sandy (mean sand content 83 and 94%) (Table 2). Mean water contents are low (0.05 g/g for both profiles) (Table 1, Fig. 6; ESM 1). Concentrations of Cl are low throughout the profiles, with no marked Cl peaks. Maximum Cl concentrations below 1 m depth are 15 and 170 mg/L. Times required to accumulate Cl in these profiles are 6.7 and 23 years, based on Cl input from precipitation (2 mg/L) and long-term MAP of 600 mm/year (Vose et al. 1998; Table 3). Accumulation times indicate that these two profiles represent entirely rain-fed conditions, according to landowner records of the timing of past irrigation practices at these sites. Calculated recharge rates for these two sites are high (61 and 94 mm/year, 10 and 16% of MAP; Table 3). Concentrations of SO_4 are similar to those of Cl, and accumulation times and recharge rates based on SO_4 are similar to those of Cl, supporting a meteoric origin of SO_4 and transport behavior similar to that of Cl in these sandy profiles (Table 3).

Two profiles are currently irrigated with fresh groundwater (E1 and E4), and another profile is currently rain-fed, although most of the profile shows the effects of past irrigation (E5). Soil texture data, only available for E1, indicate that the profile is sandy (mean sand: 84%; Table 2). Mean water contents ≥1 m are 0.06, 0.09, and 0.11 g/g, slightly higher than those under current, rain-fed cropland (Table 1, Fig. 6; ESM 2). Inventories of Cl in these profiles are 66, 100, and 120 kg/ha/m, 3–12 times higher than those of rain-fed profiles (Table 1). Maximum Cl concentrations in these irrigated profiles ≥1 m are 73, 140, and 310 mg/L. Measured Cl concentrations in groundwater samples collected from irrigation wells are 37 and 66 mg/L at the two sites that are currently irrigated (E1 and E4; ESM 1); however, these measurements may not be representative of long-term mean Cl inputs in irrigation. Concentrations of Cl in pore water are less than the value in current irrigation water at some depths in profile E1, which is attributed to years of rain-fed agriculture interspersed with irrigation. Profile E4 has pore water Cl concentrations (55–73 mg/L) similar to the current Cl concentration in irrigation water (66 mg/L), which would reflect 100% inefficiency with respect to drainage if the system were continually irrigated. However, similarity in concentrations more likely reflects predominantly rain-fed agriculture interspersed with periodic irrigation. Uncertainties in irrigation application rates make estimating recharge rates difficult. Using Cl from precipitation alone provides lower bounds on recharge of 18,

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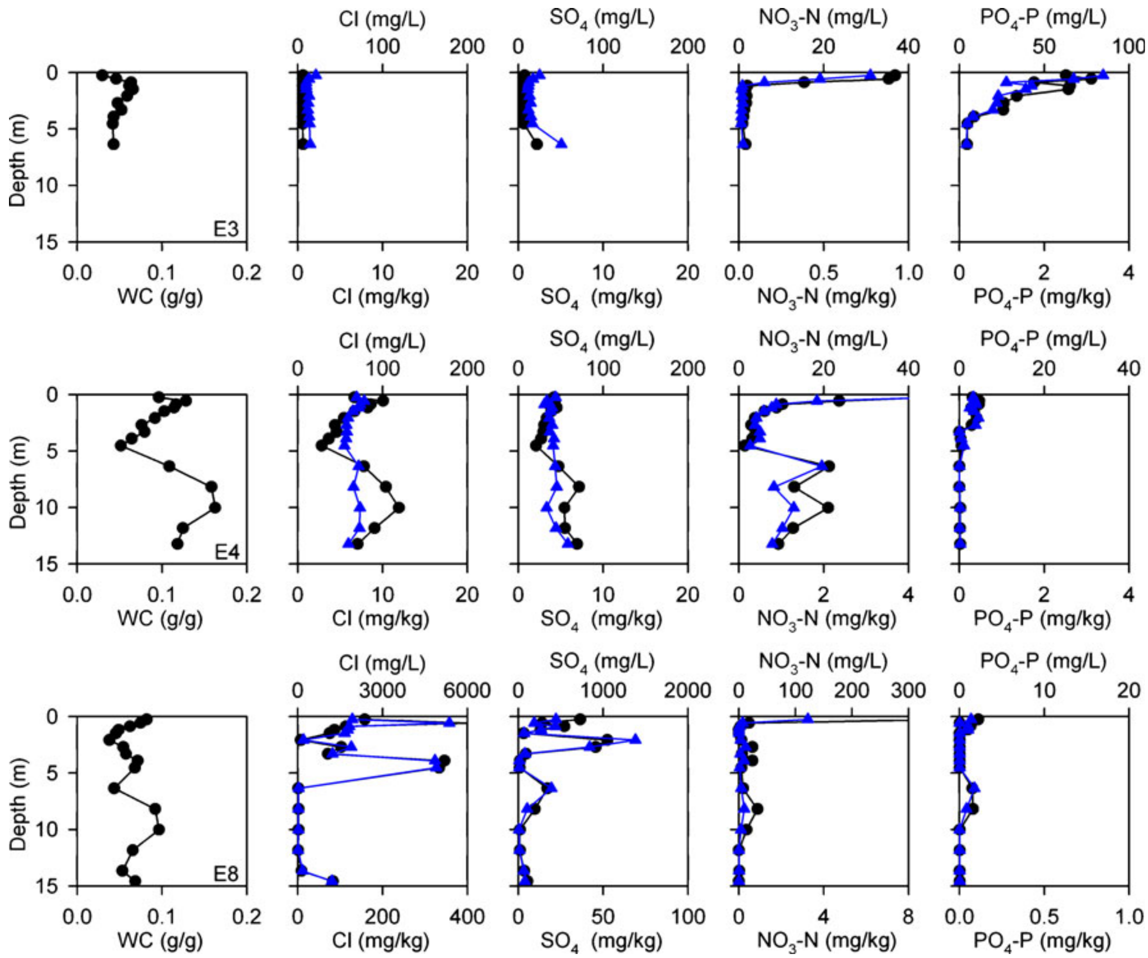

Fig. 6 Representative water content (*WC*), chloride, sulfate, nitrate-*N*, and phosphate-*P* profiles for boreholes located in the eastern study area: *E3*, rain-fed; *E4*, irrigated with fresh groundwater; *E8*, irrigated with brackish groundwater. *Black lines* and *circle symbols* represent mg/kg values. *Blue lines* and *triangle symbols* represent mg/L values. For location of boreholes, see Fig. 1

28, and 98 mm/year (Table 3). Ignoring irrigation input provides an upper bound on Cl accumulation times of 72, 87, and 140 years. Profiles of SO_4 are similar to those of Cl and result in similar recharge rates (28, 39, and 47 mm/year) for precipitation input (Table 3). Because the flux and age equations are linear, adding irrigation with higher Cl concentrations than precipitation will proportionately increase the recharge rates and decrease the accumulation times.

In the area of brackish groundwater, all three profiles (E6, E7, and E8) have generally high Cl concentrations (mean 18, 63, and 210 mg/kg, respectively), which indicates that they have been irrigated (Table 1). These irrigated profiles are not as sandy (E7: 71% and E6: 72% sand) as the other irrigated or rain-fed profiles (Table 2). Mean water contents in these profiles ≥1 m depth are moderate (0.05, 0.06, and 0.06 g/g), similar to those in rain-fed profiles and slightly lower than those in other irrigated profiles (Table 1). Inventories of Cl (290, 3,100, and 3,100 kg/ha/m) are much higher than all other profiles (Table 1). Peak Cl concentrations below the root zone (1 m) are 560, 4,900, and 6,000 mg/L and are found at depths of 1.2, 4.5, and 2.1 m, respectively (Fig. 6, ESM 3). Ignoring irrigation input to the CMB equation provides a minimum estimate of recharge rate and a maximum estimate of Cl accumulation time. Minimum recharge rates are 0.3, 5.6, and 33 mm/year (Table 3). Estimating actual recharge rates is difficult because of uncertainties in irrigation amounts and Cl concentrations in irrigation water. Chloride in the three profiles would require 350, 1,500, and 7,100 years to accumulate if precipitation provided the only input (Table 3). Groundwater sampled in one well in this brackish groundwater region near profile E8 has 850 mg/L Cl (ESM 1). Concentrations of Cl in E7 are <850 mg/L; therefore, Cl concentrations in irrigation water for this site should be <850 mg/L. Multiple Cl peaks in profile E8 suggest periods of high and low/no irrigation because soil water Cl concentrations at some depths are less than that of irrigation water if one assumes 845 mg/L for irrigation water Cl concentration (Fig. 6). A zone of low Cl concentrations (16–32 mg/L) in profile E8 from 6.4 to 13.7 m depth is attributed to a period of rain-fed agriculture. Mean recharge rate for this zone is 50 mm/year, and the time period of rain-fed agriculture is estimated to be 28 years (Table 3). This recharge rate is similar to those under other rain-fed profiles (Table 3).

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At rain-fed sites, concentrations and inventories of NO_3 and PO_4 are highest in the root zone (≤1 m) and generally much lower at depth, indicating minimal leaching of these nutrients. Profile E3 is unusual in that high PO_4 concentrations extend to ~4 m depth, decreasing from 43 mg/L at 1.2 m to 8 mg/L at 3.9 m depth (Fig. 6). At sites irrigated with fresh groundwater (E1, E4, and E5), inventories of NO_3–N are much higher than those beneath rain-fed agriculture, both within (≤1 m depth; 3–13 times higher) and below (22–75 times higher) the root zone (Table 1). Inventories of NO_3 within the root zone are similar or slightly higher than those below the root zone (3–7 times), indicating some leaching of NO_3 below the root zone. Inventories of PO_4 are mostly in the root zone and are similar to or slightly higher than those under rain-fed cropland (Table 1). These differences in nutrient levels between irrigated and rain-fed agriculture are attributed to NO_3 in irrigation water (9 and 13 mg NO_3–N/L in freshwater and 10 mg NO_3–N/L in brackish water, ESM 1) and fertilizer application in irrigated sites. In contrast, PO_4 concentrations in irrigation water are low (<0.01–0.03 mg PO_4–P/L in all samples). At sites irrigated with brackish groundwater, NO_3–N inventories in the root zone have a similar range to those under the other irrigated sites and are as much as 8 times lower below the root zone (Table 1). Inventories of PO_4 are also lower within and generally below the root zone (Table 1).

The recharge estimates from this study provide some indication of how much groundwater can be extracted for irrigation without mining the aquifer. Recharge rates under rain-fed agriculture (50–120 mm/year), which are considered the most reliable, could support 300 mm/year of irrigation over ~20–40% of cultivated land. These calculations address sustainability from the point of view of water quantity but do not assess water quality issues. Water quality should not be an issue in the area of fresh groundwater. Although brackish groundwater could degrade the soils because of salinity buildup, rotation with rain-fed agriculture should reduce this problem. Maintaining groundwater quality in terms of total salinity in the area of brackish groundwater is not an issue because it is already of low quality.

Modeling of recharge in the eastern study area

Unsaturated zone water fluxes were simulated for rain-fed sites in the eastern study area (E2, E3). The simulation period (24 February 2000–2007) has 29% lower MAP (431 mm/year) from GLDAS than the long-term MAP for Jaipur (604 mm/year, 1868–2000); therefore, GLDAS precipitation estimates for the simulation period may not be representative of the long-term MAP. No station records are available for Jaipur for 2001–2007 to scale GLDAS precipitation estimates. Various scenarios were simulated to evaluate sensitivity of recharge estimates to different vegetation parameters. Simulated recharge for bare soil is 132 mm/year, which can be considered an upper bound on actual recharge for this time period. Crops were simulated using a maximum leaf area index of 2.0. Simulated rooting depths included 0.5, 1.0, 1.5, and 2.0 m, and corresponding recharge rates are 110, 89, 84, and 70 mm/year. A rooting depth of 1 m is generally considered representative of typical crops in this region. Recharge occurs during the monsoon period. Annual recharge was spread throughout the simulation period and generally varied with annual precipitation (r=0.79). Simulated recharge rates are generally consistent with CMB-based recharge estimates from rain-fed agricultural sites of 61–90 mm/year (E2 and E3) and from sections of profiles that represent rain-fed conditions in currently irrigated sites (E8: 50 and E5: 120 mm/year; Table 3).

Comparison with recharge estimates from previous studies

Recharge rates from the arid western sites in the Thar Desert are consistent with recharge estimates from similar regions globally, including those in the Badain Jaran desert in N. China with predominantly Asian summer monsoon precipitation (CMB recharge, 1.4 mm/year; 1.7% of MAP (84 mm/year; Gates et al. 2008). In contrast, there is no recharge in (semi)arid regions in perennially vegetated, semiarid regions in the southwestern USA, based on Cl and pressure data (Phillips 1994), or in revegetated areas of the Tengger Desert (China), based on lysimeter monitoring (1990–1995)—MAP 174 mm/year (Wang et al. 2004).

Recharge rates in the eastern study area near Jaipur were compared with those of other cultivated regions. Previous recharge studies in northwestern India in 1972–1973 and in 1994–1995 used injected tritium to estimate recharge rates in rain-fed grassland settings (Rangarajan and Athavale 2000). Median recharge rates were 35, 43, and 67 mm/year at different sites, representing 8, 9, and 14% of precipitation (460, 470, and 491 mm), respectively. These recharge rates are within the range of those estimated for rain-fed agriculture in the eastern study area (Table 3). Subsurface distribution of bomb tritium was used to estimate recharge in a study conducted in 1967 and 1969 at six sites in the neighboring state of Gujarat (Sukhija and Shah 1976). Three of the six sites are similar to the eastern study area, with similar or lower precipitation rates of 455, 500, and 605 mm/year. Recharge rates at these sites are 15, 15, and 26 mm/year, representing 3, 3, and 4% of precipitation, respectively, lower than the estimates from rain-fed agriculture in this study.

Recharge rates under rain-fed cropland in the eastern study area (50–120 mm/year; 8–20% of MAP) are slightly higher than recharge rates in deep sands in northwestern Senegal (30 mm/year; ~10% of MAP of 290 mm/year; Gaye and Edmunds 1996) and slightly higher than recharge rates in the Southern High Plains, USA (24 mm/year, 5% of MAP of 450 mm/year; Scanlon et al. 2007b), and southwestern Niger in Africa (25 mm/year; 4% of MAP of 557 mm/year; Favreau et al. 2009). The slightly higher recharge rates may be related to higher MAP than Senegal and to the intensity of the summer monsoon in the eastern study area and more sandy soils relative to more evenly distributed summer precipitation in the Southern High Plains and Niger regions

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and less sandy soils. It is more difficult to compare recharge rates beneath irrigated sites because of variations in irrigation application rates.

Comparison with nutrient inventories from previous studies

Nutrient availability in the Thar Desert was also compared with that of other regions. Many desert regions have high NO_3 concentrations under native vegetation. Examples include regions within the southwestern USA, where peak inventories are as much as 10,000 kg N/ha and NO_3 is attributed to accumulation from atmospheric deposition during the past 10,000–15,000 years (Walvoord et al. 2003). Peak concentrations are as much as 3,100 mg NO–N/L at 2.8 m depth. In contrast, some regions in the southwestern USA have very low NO_3 inventories under native vegetation, e.g., 24–76 kg N/ha, Southern High Plains, USA (McMahon et al. 2006; Scanlon et al. 2008). Large NO_3 reservoirs have also been found in semiarid regions in Senegal (≤1,000 kg N/ha), which are attributed to N fixation by native trees (Deans et al. 2005). The lack of accumulation of NO_3 in soils in the Thar Desert from atmospheric deposition may be attributed to downward movement of NO_3 caused by recharge.

Information on NO_3 levels beneath rain-fed agriculture is limited. Moderately high NO_3–N inventories (3–578 kg/ha/m) beneath rain-fed agriculture in the Southern High Plains (USA) have been attributed to mineralization and nitrification of soil organic nitrogen associated with initiation of cultivation and application of inorganic fertilizers (Scanlon et al. 2008). Inventories of NO_3–N beneath irrigated agriculture are generally high (620–1,800 kg/ha) throughout the USA High Plains because of higher NO_3 application in irrigated sites (McMahon et al. 2006). In contrast, NO_3 inventories in the eastern study area in Rajasthan beneath rain-fed agriculture and brackish irrigated agriculture are much lower (Table 1) and indicate that crop yield may be increased with additional fertilizer application.

Future studies

Work conducted in this study represents an initial reconnaissance to develop a conceptual understanding of recharge and nutrient cycling and initial estimates of recharge rates and nutrient inventories. The exercise points out a number of gaps in our knowledge that may be addressed in future studies. The CMB approach provides qualitative and quantitative information on recharge rates; however, information on Cl inputs is limited. Precipitation chemistry data would be valuable in reducing uncertainties in recharge rates that are based on the CMB approach. In addition, distinction between wet and dry fallout is important for providing data on Cl concentrations in bulk precipitation, which is required for the CMB approach. Results of this study also suggest that SO_4 may be a useful indicator of recharge; therefore, data on SO_4 concentrations in bulk precipitation would also be valuable. Monitoring irrigation water application rates and measuring salt concentrations in irrigation water are essential prerequisites for estimating recharge rates under irrigated sites. Recharge rates in dune/interdune settings in the western study region depend on accurate soil moisture data. The very sandy nature of the sediments may have resulted in drying during sample collection and processing. Installing soil moisture sensors would avoid some of these problems; however, installation and maintenance of monitoring stations in these remote regions are generally difficult.

Understanding nutrient availability and sources of nutrients is essential for optimal crop production. Natural accumulation of NO_3 is low in these sandy soils, suggesting that NO_3 levels might be limiting crop production in rain-fed agriculture in cultivated regions. Levels of PO_4 are variable; however, future studies should address sources of PO_4, such as precipitation and mineral dissolution. Soil organic nitrogen (SON) levels should be measured in natural and cultivated regions, and the potential for mineralization and nitrification of soil organic nitrogen should be examined. This source of NO_3 is relied on solely in rain-fed agriculture in some regions of western Canada in the past and also in parts of the USA High Plains (Schimel et al. 1985; Tisdale et al. 1985). Carbon sequestration in soils through agricultural practices, i.e., minimum or no tillage and management of crop residues, could increase SON levels and may result in increased NO_3 levels in soils. Assessing nutrient requirements for irrigated agriculture is essential to ensuring that crop yield is maximized and not susceptible to nutrient limitations. Quantifying NO_3 levels in irrigation water and mineralization and nitrification of SON will be valuable in determining fertilizer requirements for crop production.

Conclusions

In the western study area of the Thar Desert near Jaisalmer in sparsely vegetated dune/interdune settings, estimated recharge rates are low (2.7–5.6 mm/year), 2–3% of MAP (165 mm/year). However, these estimates may be underestimated somewhat because of potential drying of sandy soils during collection and processing. High Cl concentrations beneath a plantation adjacent to a canal are attributed to irrigation, and the Cl bulge suggests that recharge is minimal or nonexistent. Nutrient inventories in the western study area are low within (NO_3: 5–28 kg N/ha) and below (NO_3: 0–14 kg N/ha/m) the root zone, indicating lack of N fixation by sparse vegetation or lack of NO_3 buildup from meteoric input of NO_3. Inventories of PO_4 are also low.

In the eastern study area along the margin of the desert near Jaipur, soil profiles in rain-fed cultivated agriculture have low mean Cl concentrations (13 and 29 mg/L) below the root zone (1 m depth), indicating high recharge rates of 61 and 94 mm/year, 10–16% of MAP (600 mm/year). Areas irrigated by fresh groundwater have profiles with low mean Cl concentrations (66, 68, and 86 mg/L), whereas areas irrigated by saline groundwater have profiles with much higher Cl concentrations (280, 970, and 3,900 mg/L). The large salt accumulations in the area irrigated by brackish groundwater would require 350, 1,500, and 7,100 years to accumulate if precipitation provided the only Cl input. Estimating recharge rates under irrigated cropland is difficult because of uncertainties in irrigation amounts and irrigation water quality. Minimum recharge rates based on precipitation input alone are 18, 28, and 98 mm/year in the area of fresh groundwater and 0.3, 5.6, and 33 mm/year in the area of brackish groundwater. The two profiles with higher recharge rates (98 and 33 mm/year) reflect periods of rain-fed agriculture with associated recharge rates of 50 and 120 mm/year, similar to those under current rain-fed agriculture. Nutrient levels are higher in the root zone under rain-fed and irrigated cultivated sites and much lower at depth. The generally low nutrient levels beneath rain-fed agriculture and agriculture irrigated with brackish groundwater do not provide evidence of mineralization and nitrification of soil organic nitrogen. Crop production may benefit from additional fertilizer inputs, particularly in rain-fed and some irrigated areas. Recharge rates near Jaipur are similar to recharge estimates from previous studies in that region, based on tritium injection. Two to five times higher recharge rates under rain-fed cropland near Jaipur relative to rain-fed cropland in many semiarid regions (Southern High Plains, USA; SW Niger) may be attributed to higher MAP than Senegal and to the very sandy nature of the soils and intensity of summer monsoon precipitation in the Jaipur region. Recharge rates of 50–120 mm/year under rain-fed agriculture indicate that irrigation of ~20–40% of cultivated land with 300 mm/year should be sustainable from a water-quantity perspective.

Results from this study suggest that the CMB approach provides reliable recharge rates for rain-fed agriculture and bounding estimates for irrigated agriculture in the eastern study area. Similar recharge rates based on SO_4 increase confidence in these recharge estimates. Modeling analyses based on available climatic forcing data and estimates of soil hydraulic properties suggest that recharge estimates based on the tracer data are reasonable.

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