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Key Points:

- Tracers reveal low regional anisotropy in the sedimentary aquifer system of NW India
- Local meteoric recharge sources dominate in both shallow and deep aquifers
- Evidence of enhanced modern recharge at depth due to intensive abstraction

Supporting Information:

- Texts S1–S6, Figures S1–S8, and Tables S1–S4

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Groundwater recharge and age-depth profiles of intensively exploited groundwater resources in northwest India

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Abstract Intensive irrigation in northwest India has led to growing concerns over the sustainability of current and future groundwater abstraction. Environmental tracers and measurements of groundwater residence times can help quantify the renewal processes. Results from 16 paired locations show the interquartile ranges for residence times in shallow alluvial groundwater (8–50 m deep) to be 1–50 years and significantly less than those from deeper groundwater (76–160 m deep) at 40–170 years. The widespread occurrence of modern tracers in deep groundwater (>60% of sites had >10% modern recharge) suggests that there is low regional aquifer anisotropy and that deep aquifers are recharged by a significant component of recent recharge via vertical leakage. Stable isotope and noble gas results at all depths conform to modern meteoric sources and annual average temperatures, with no evidence of significant regional recharge from canal leakage in this study area close to the Himalayas.

1. Introduction

Unsustainable abstraction of groundwater for irrigation and food production continues to be a global water resource challenge facing many alluvial aquifer systems [*Foster and Chilton*, 2003]. The semiarid terrain of northwest India is a prime example of this, being home to over 100 million people and a major area for wheat, rice, and sugar cane cultivation. Population densities in Punjab and Haryana are greater than 500 people per km^2 and are among the most agriculturally productive states in India [*Mukherjee and Kuroda*, 2003]. The sustained growth in the agricultural sector has only been possible through the use of irrigation from shallow (typically <50 m deep) local groundwater sources as well as an extensive canal network that redistributes water from the Himalayan watershed to the plains. Recent satellite-based observations have shown that there is currently a significant net loss in terrestrial water storage (TWS) in this region [*Rodell et al.*, 2009; *Tiwari et al.*, 2009]. This approach has been useful as part of large-scale assessments of changes in TWS, but there is a high degree of spatial heterogeneity in groundwater recharge processes that is masked by this large-scale regional approach. Characterizing and understanding the reasons for this local heterogeneity are fundamental to begin to develop effective water management plans. This requires higher-resolution field-based observations.

Groundwater levels have been falling in parts of this region for at least the last two decades due to intense groundwater abstraction, demonstrated locally using direct observation of premonsoon groundwater levels [*Fishman et al.*, 2011; *CGWB-Central Ground Water Board*, 2011] as well as regional-scale modeling studies [*Cheema et al.*, 2014]. By contrast, there are areas in close proximity to canal networks with evidence of recharge from the leaky canal system based on groundwater level observations [e.g., *Kumar et al.*, 2011]. Some studies across the Indo-Gangetic Basin have found that intensive pumping may actually enhance post-monsoon recharge [*Chaturvedi and Srivastava*, 1979; *Shamsudduha et al.*, 2011]. The spatial variation in the relative importance of meteoric sources of recharge and redistributed surface water recharge, (from natural drainage and canal losses from Himalayan meltwater and runoff sources) for sustaining groundwater resources is currently poorly understood. Understanding the distribution of these recharge processes, is key to assessing the resilience of groundwater resources to over abstraction.

The "plains aquifer" of northwest India is best considered an aquifer system, comprising layered sand and gravel deposits vertically separated by thick low-permeability (*K*) horizons [*Bowen*, 1985]. The complex geomorphological evolution of this alluvial aquifer system has resulted in a high degree of both vertical and horizontal heterogeneity [*Bowen*, 1985; *Phadtare*, 1985; *Samadder et al.*, 2011]. Regional hydraulic anisotropy (ratio horizontal to vertical permeability) is a major factor in controlling the hydraulic connectivity of shallow and deep groundwater in large unconsolidated sedimentary aquifer systems [*Cardenas and Jiang*, 2010; *Jiang et al*., 2010; *Gassiat et al*., 2013] and the resulting evolution of groundwater age profile due to pumping [*Hoque and Burgess*, 2012]. In Bangladesh, within the distal part of the Indo-Gangetic alluvial aquifer system, high regional hydraulic anisotropy has played a pivotal role in protecting deeper groundwater from being contaminated with shallow arsenic contaminated groundwater [*Michael and Voss*, 2009].

Chemical and isotopic properties of groundwater are used as environmental tracers and enable assessments of residence time and recharge sources to be made. The use of CFCs and SF_6 as age tracers in groundwater is based on their rise in atmospheric concentrations over the last 50 years and assumptions about atmospheric mixing and recharge solubility [*Cook and Böhlke*, 2000; *Plummer et al*., 2001]. Each tracer may have limitations in their application for estimating groundwater residence times [*Darling et al*., 2012], in particular, the CFCs may be affected by pollution and/or degradation under anaerobic conditions [e.g., *Lapworth et al*., 2013], and SF_6 can be problematic in some settings due to terrigenic production [*Koh et al*., 2007].

Interpreting trace gas indicators relies on consideration of mean recharge temperature, altitude, and incorporation of excess air. The phenomenon of "excess air" incorporated during recharge has an insignificant effect on the CFCs but a larger effect on SF_6 [*Plummer et al*., 2001]. Lumped parameter models (LPM) typically used to describe some of the variation seen in groundwater mixtures include the piston flow model, exponential mixing model, partial exponential model (PEM), dispersion model (DM), and binary mixing models, i.e., the combined use of two flow models [*Zuber*, 1986; *Maloszewski and Zuber*, 1996; *Cook and Böhlke*, 2000; *Suckow*, 2014]. In some instances, it is possible to use two tracers with different input functions to assess which mixing model to use for estimating mean residence times (MRT), e.g., SF_6 and CFC-12.

The noble gases Ne, Ar, Kr, and Xe can be used to estimate groundwater recharge temperatures. Their dissolved concentrations are considered to be controlled by the average temperature at the water table during recharge, based on assumptions regarding their solubility equilibrium with water [e.g., *Stute and Schlosser*, 1993, 2000; *Stute et al*., 1995; *Wieser et al*., 2011]. They also enable the quantification of excess air, i.e., the forcible solution of air bubbles resulting from movements of the water table [*Osenbrück et al*., 2009].

A comprehensive suite of environmental tracers are used for the first time to investigate the hydrogeology of the alluvial aquifer system of northwest India that has experienced sustained increases in groundwater use over the last four decades. The aim of this paper is to use these tracers to characterize age distributions, sources of recharge, and assess the vulnerability of the deep aquifers to the migration of contamination to depth and their long-term resilience to anthropogenic pressures. Tracer data from areas with contrasting long-term trends in premonsoon water level are compared to assess the impact of pumping on recharge processes. Environmental tracers are also used to investigate the occurrence of low flow/stagnant zones which may contain high residence time groundwater within unconsolidated sedimentary settings [e.g., *Mazor*, 1995; *Fridman et al*., 1995; *Maloszewski et al*., 2004].

2. Methods

Water stable isotopes are tracers of the physical processes that water molecules undergo between evaporation from the ocean and arrival in the aquifer via recharge [*Clark and Fritz*, 1997; *Edmunds and Wright*, 1979]. Long-term average amount-weighted isotope values for precipitation have been used to compare with groundwater isotope values to understand recharge sources and processes [e.g., *Grabczak et al*., 1984; *Harrington et al*., 2002; *Négrel and Giraud*, 2010]. The depleted δ^2H and δ^{18}O signatures in canal and surface drainage water from Himalayan sources compared to the local meteoric monsoon signature make this a useful tracer for assessing the significance of canal water sources in shallow groundwater recharge in this region [*Datta et al*., 1996; *Rao et al*., 2014].

SF_6 data from this aquifer were found to be significantly contaminated with terrigenic sources and not suitable for groundwater dating (see supporting information). In light of this, only CFC data were used for groundwater dating and mean residence times were estimated using two plausible mixing models; PEM and DM (with a dispersion parameter of 0.5) have been used for comparison. These two models were used based on realistic conceptual models which include considerations of groundwater flow, well-field configuration, lithological controls, and borehole screening.

Groundwater from boreholes that is partially screened (screens sections may be up to 20 m) is likely to be a mixture of groundwater ages with different flow paths [*Suckow*, 2014]. A limitation of using these tracers is that they are not able to trace mixing of waters older than 60 years. Therefore, estimated calculated mean ages are susceptible to nonlinear mixing within groundwater of older but indeterminate age [e.g., *Waugh et al.*, 2003; *Solomon et al.*, 2010; *Koh et al.*, 2012]. Further explanation and justification for the use of these models, and schematic diagrams giving example borehole configurations (Figure S1), are provided in the supporting information.

Stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$) was carried out using standard preparation techniques followed by isotope ratio measurement on a VG-Micromass Optima mass spectrometer. Data considered in this paper are expressed in ‰ with respect to Vienna Standard Mean Ocean Water. CFCs and SF_6 were measured by gas chromatography with an electron capture detector after preconcentration by cryogenic methods, based on the methods of *Busenberg and Plummer* [1992, 2000]. Measurement precision was within ±0.1‰ for $\delta^{18}O$, ±1‰ for $\delta^{2}H$, and ±5% for the CFCs, with detection limits of 0.01 pmol/L (CFC-12), 0.05 pmol/L (CFC-11), and 0.1 fmol/L (SF_6). Measurement of stable isotopes and CFCs took place at British Geological Survey laboratories in the UK. An average annual air temperature of 23°C was used for this study, based on local meteorological data [*NRK, Norwegian Meteorological Institute*, 2015], and the altitude for the region is <500 masl. The U.S. Geological Survey (USGS) TracerLPM program was used to estimate groundwater MRTs [*Jurgens et al.*, 2012].

Noble gas concentrations were analyzed using a quadrupole mass spectrometer. Using Ne, Ar, and Kr input data, recharge temperatures and excess air were estimated using a range of interpretive physical models, a least squares inverse modeling program [*Aeschbach-Hertig et al.*, 1999]. Closed equilibrium (CE) and the partial reequilibrium model (PR) were used to interpret the noble gas temperature data, further details on models used can be found in the supporting information. A total of 44 sites from Central Groundwater Water Board (CGWB) monitoring stations across the study area (each with a record >15 years, and typically >20 years) were used to assess the spatial variation in long-term groundwater water level records (range 1985–2012). Following quality control of raw data, water level records from manual dips taken in May were used to establish long-term trends in premonsoon water levels. See supporting information for further details.

A systematic sampling campaign was carried out across the Bist-Doab region of Punjab, northwest India, a 9000 km^2 area located between the R. Sutlej, R. Beas, and the Shiwalik hills to the north. This area is an ideal observatory to understand the impacts of intensive groundwater abstraction on groundwater flow and recharge processes: it is among the most productive areas in Punjab with annual average rainfall of ~700 mm that is highly dependent on groundwater irrigation (75% groundwater irrigation and 25% surface water irrigation) and has seen groundwater levels fall systematically in some regions over the last two decades [*Cheema et al.*, 2014; *Lapworth et al.*, 2014]. An array of sites were distributed across the study area to characterize a range of hydrogeological settings including conventional recharge zones, the midplains, and discharge zones close to the confluence of the R. Satluj and Beas (see supporting information for further details including Figure S2 which shows a schematic cross section of the upper Indus and Ganges Basins, and Figure S8 for site locations). These were sampled for a range of environmental tracers to characterize the top 160 m of the alluvial aquifer system. At 16 locations, paired shallow (8–50 mbgl) and deep (>76–160 mbgl) boreholes were sampled from aquifers (sand and gravels) separated by thick (typically several, 10–20 m) lower permeability horizons. Canal samples and high-frequency precipitation samples (2009–2013) from across the catchment were also sampled and analyzed for stable isotopes for comparison. Sampling for groundwater CFCs and stable isotopes was carried out both premonsoon and postmonsoon (2013–2014) to characterize temporal variability. Premonsoon samples for noble gases were obtained from a subset of sites.

3. Results

Summary results of groundwater CFC-12 concentrations are shown as boxplots in Figure 1a, and estimated MRTs using the CFC-12 tracer data using two LPMs (PEM, DM) are shown as boxplots in Figures 1b and 1c. The deeper sites were found to have significantly lower CFC concentrations compared to shallow sites and corresponding significantly higher MRTs ($p < 0.001$, Wilcoxon rank sum test). CFC contamination was not found to be a major issue in this study. Only two deep sites had no detectable CFC-12 tracer. Shallow samples that showed evidence of CFC-12 contamination with concentrations higher than current recharge ($n = 7$, <10%) were omitted from the analysis. CFC-11 concentrations were found to be low relative to CFC-12 likely

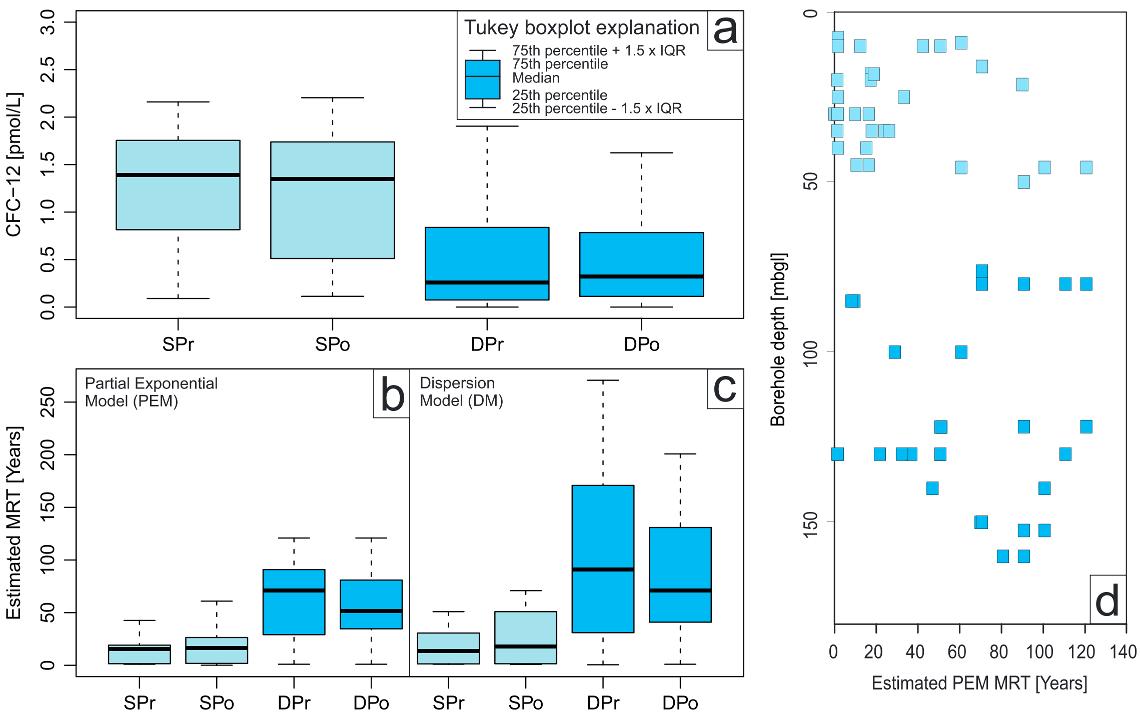

Figure 1. Residence time tracer results: (a) summary of groundwater CFC-12 concentrations, (b) estimated MRTs for shallow and deep groundwater samples using a partial exponential model, (c) estimated MRTs for shallow and deep groundwater samples using a dispersion model, and (d) variation in MRT (PEM estimates) with depth SPr = shallow groundwater premonsoon, SPo = shallow groundwater postmonsoon, DPr = deep groundwater premonsoon, and DPo = deep groundwater postmonsoon. Over modern values have been excluded from the analysis. Data shown from 16 paired boreholes, where shallow (8–50 mbgl) and deep (>76–160 mbgl), sampled premonsoon and postmonsoon.

due to degradation (see supporting information Table S1) and were not used for estimating MRTs. There was no significant difference found ($p > 0.4$, Wilcoxon rank sum test) for MRT distributions in either shallow or deep groups for premonsoon and postmonsoon campaigns for PEM and DM estimates. Results from the DM did, however, produce older estimates (larger interquartile range) for waters with concentrations levels of tracer due to underlying model assumptions. Overall, based on PEM and DM estimates, the shallow boreholes (8–50 mbgl) were found to have MRTs with a range 1–50 years (interquartile range), while in deeper boreholes (76–160 mbgl) have MRTs with an interquartile range of 40–170 years.

Figure 2a shows the spatial distribution of MRT for deep sites and the depth normalized ΔMRT (yr/m) = (MRT2 − MRT1)/(d2 − d1), where d1 and d2 are the completion depths for the shallow and deep sites and MRT1 and MRT2 are their respective mean residence times. The long-term trends (1985–2012) in premonsoon shallow groundwater levels across the study area are shown in Figure 2b. There is an overall increase in long-term premonsoon decline in groundwater toward the confluence zone, with sites close to the break in slope and Shiwalik hills or close to surface water courses in some cases show no overall long-term trend in groundwater level, and in several cases moderate increases in groundwater levels over the last two decades (Figure 2b). Largest declines in groundwater level were found in the central plain area close to Jalandhar and Kapurthala. Estimated MRTs are younger for deep groundwater in the plains region compared to sites close to the Shiwalik hills (Figure 2a) which are conventionally considered recharge zones. Moreover, the difference between the shallow and deep MRTs suggests that while this is highly spatially variable there is a convergence between shallow and deep MRTs in the plains region and specifically in areas within close proximity to the large urban centers of Jalandhar, Kapurthala, and Nawanshahr (Figure 2). Here there is greater pumping from the deep part of the aquifer system and overall the greatest long-term declines in the phreatic water level.

There is no significant difference (Wilcoxon rank sum test) in premonsoon and postmonsoon stable isotope distributions (δ^2H and δ^{18}O) for either shallow (e.g., $p = 0.54$ for δ^2H) or deep groups ($p = 0.86$ for δ^2H). However, a significant difference between shallow and deep distributions was found ($p = 0.04$). Distinct signatures for canal and river waters are found which do not overlap with either shallow or deep

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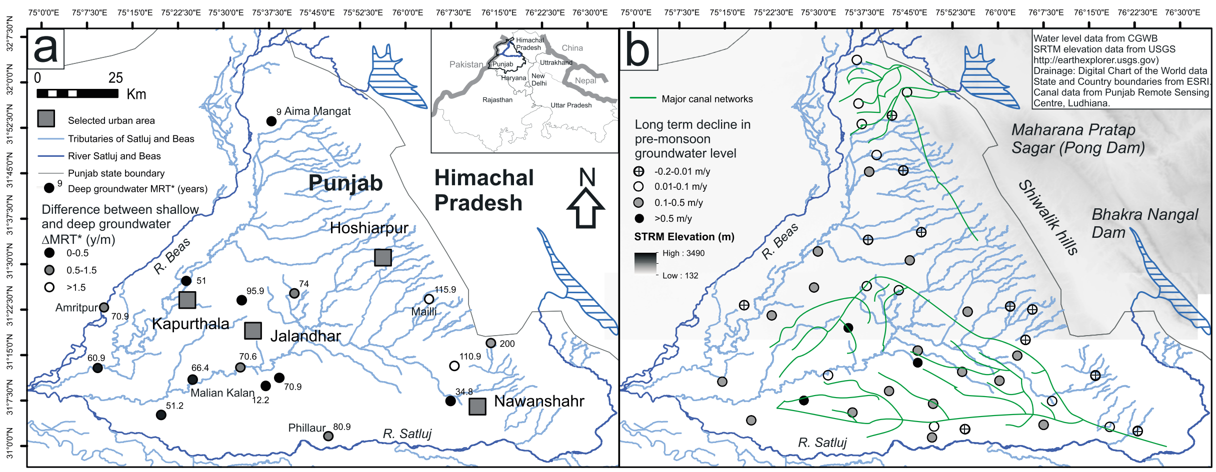

Figure 2. (a) Spatial variation in ΔMRT (yr/m) and deep MRT (years) across the study area, (b) long-term decline in premonsoon groundwater level from CGWB data (1985–2012) using regression analysis for premonsoon shallow groundwater levels, see supporting information for details (Figure S6). Surface drainage, surface relief (USGS STRM data), and the regional extent of the canal irrigation network are also shown. ΔMRT (yr/m) is the depth normalized difference between the shallow and deep MRT (PEM estimates) given as ΔMRT = (MRT2 − MRT1)/(d2 − d1) where d1 and d2 are the completion depths for the shallow and deep sites and MRT1 and MRT2 are their respective mean residence times.

groundwater signatures (see Figures 3a and 3b). Regression lines for groundwater are close to the regional meteoric water line, and there is some evidence of evaporative enrichment in a few shallow groundwater and canal samples. There is only a small general trend of lower δ^2H signatures with depth (Figure 3c) (this trend is more clearly demonstrated on a site basis in Figure S3 in the supporting information), but consistent *d*-Excess values, most of which fall between +5 and +10 (see Figure S5). Groundwater δ^2H and *d*-Excess signatures conform to modern monsoon ranges (Figure 3d), and the δ^2H data suggest that groundwater recharge is dominated by local meteoric sources and is also consistent with long-term amount-weighted mean precipitation values for δ^2H and *d*-Excess (Figures 3c and 3d).

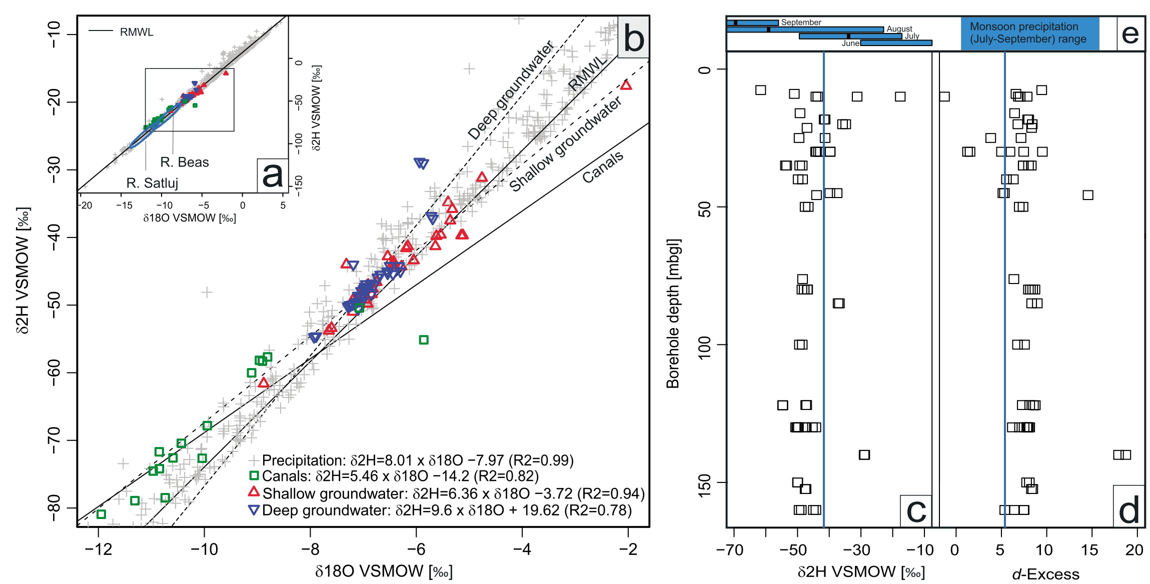

Figure 3. (a) Cross plot of δ^{18}O versus δ^2H for groundwater, canals, and precipitation within the study area. Full precipitation data shown in inlay with ranges for River Satluj and River Beas for comparison [*Rao et al.*, 2014]. (b) Cross plot of δ^{18}O versus δ^2H for data extent for groundwater and canal points, (c) depth variation in δ^2H for groundwater and solid line shows amount-weighted δ^2H for precipitation, (d) depth variation in groundwater *d*-Excess ($d = \delta^2H - 8*\delta^{18}O$) [*Dansgaard*, 1964] and solid line shows amount-weighted δ^2H and *d*-Excess for precipitation, (e) median and interquartile ranges for local precipitation data, and monsoon (June–September) precipitation ranges for *d*-Excess—note *x* axis on same scale as for Figures 3b and 3c. Robust regression line are shown for precipitation, canal water, shallow groundwater, and deep groundwater samples. Measurement precision (1σ) was within ±0.1‰ for δ^{18}O and ±1‰ for δ^2H, symbol size for Figure 3c represents typical measurement error for δ^2H. Groundwater data are from 16 paired locations where shallow (8–50 mbgl) and deep (>76–160 mbgl) boreholes were sampled premonsoon and postmonsoon, canal data from 16 sites, rainfall data from 13 sites, all within the study area.

Table 1. Groundwater Noble Gas Recharge Temperatures (NGT), Excess Air, and MRT Estimates[a]

Model Sample-Depth (mbgl)	Closed System Equilibrium NGT (°C)	± (°C)	Excess air % ΔNe (%)	PEM MRT[c] (years)
Amritpur-7.6	21.8	0.6	2.4	1.8[d]
Amia Mangat-20	24.9	0.8	0.3	1.5[d]
Phillaur-35	19.7	0.6	17.1	1.5[d]
Amritpur-76	22.1	1.7	25.5	71
Mailli-80	21.2	1.0	15.1	111
Phillaur-80	18.0	1.1	12.9	71
Aima Mangat-85	21.6	0.2	19.2	NA
Malian Kalan-130	21.5	0.4	76.7	110
Mean[b]	21.3 ± 2			

[a]NGT = noble gas temperature (°C) derived from dissolved noble gases using the closed system equilibrium model in Noble90. Excess Air = forcibly dissolved air expressed in terms of Ne supersaturation. Temperature errors are shown as ± 1σ.
[b]Geometric mean and ±1σ.
[c]MRT (years) results estimated using the Partial Exponential Model for CFC-12 data.
[d]CFC-12 data for these samples are very close to modern atmospheric concentrations.

Table 1 summarizes noble gas results, noble gas recharge temperatures (NGT), and associated errors, excess air ΔNe (%), and MRT estimates using the PEM for comparison. Noble gas data are presented for the closed system equilibrium (CE) model, (PR estimates of NGT can be found in the supporting information (Table S2)). Overall, both the CE and the PR models show comparable results, i.e., close to or within error for most sites (see supporting information). Recharge temperatures range from 17.1 to 24.9°C with an average value of 21.3 ± 2 for the CE model.

The unfractionated CE model gave the lowest temperature errors ($<$±2° C) and is thought to best represent physical processes during recharge [*Kipfer et al*., 2002] and was therefore the preferred approach. Excess air values vary considerably with a range of 0.3–77 ΔNe % for the CE model. Results from boreholes between 35–85 mbgl show comparable results (13–25% ΔNe), and generally there is an increase in excess air with borehole total depth and MRT (Table 1).

4. Discussion

4.1. Dominance of Modern Local Meteoric Sources of Groundwater Recharge

The contrasting isotope signatures of the two main potential sources of recharge, precipitation, and surface waters in this area clearly demonstrate that both shallow and deep regional groundwater recharge is dominated by local modern meteoric sources, rather than surface water sources including canal irrigation water (Figure 3a). Given the widespread canal coverage in this region, this is an important finding and contrasts with other areas in northwest India where canal return recharge is thought to dominate regional shallow groundwater recharge [*Kumar et al*., 2011]. The depleted δ^2H signatures in the deep groundwater relative to the shallow groundwater (see Figure S3) can be explained in terms of recharge sources from $>$50 mbgl having a component of groundwater recharged some distance up gradient from the sampling point at a higher elevation. Alternatively, this may be indicative of modern groundwater irrigation and the recycling of groundwater over the last four decades leading to a small δ^2H enrichment in the shallow aquifer system due to evaporative processes (Figure S5). Even at a depth of 160 m, groundwater isotope signatures are consistent with local modern rainfall sources (Figures 3a and 3c) and together with the NGT and δ^{18}O results from this study suggest that paleowater [e.g., *Wieser et al*., 2011], if present in this region, is deeper than 160 mbgl.

By comparing groundwater and precipitation isotope signatures, which have a significant seasonal variation due to the monsoon cycle [e.g., *Datta et al*., 1991; *Krishan et al*., 2013; *Lekshmy et al*., 2014], and the amount-weighted values for this region, we are able to show that groundwater recharge is dominated by local modern meteoric sources. There are a few shallow groundwater samples and one canal sample which deviate from the regional meteoric water line (Figure 3b), which indicate significant evaporative enrichment prior to recharge, but our study suggests it is not a widespread phenomenon in this area.

Average noble gas recharge temperatures for groundwater were found to be 21.3 ± 2.0°C which is consistent with current annual average air temperatures of 23°C for this region [*NRK*, *Norwegian Meteorological Institute*, 2015]. There is no obvious variation in NGT with depth. This is in contrast with results from the sedimentary aquifer system farther south in the arid terrain of Gujarat where noble gas and stable isotope data showed evidence for changes in climatic conditions, with paleowaters up to 50,000 years found at comparable depths [*Wieser et al.*, 2011]. There is some variation in excess air with depth, with shallow modern groundwater showing reduced excess air (0.3–2.4% ΔN‰) compared to intermediate (13–25% ΔN‰) and deeper samples 77% ΔN‰, see Table 1. These results are consistent with the long-term water table variations (Figure 1b) which show that sites close to the Shiwalik hills (Aima Mangat and Mailli) and surface waters (Phillaur and Amritpur) have much lower long-term water table declines (see Figure 2b and supporting material) and are therefore likely to have less potential for incorporating excess air compared to sites in the central plain area such as Millian Kalan which are impacted by intensive pumping which induce greater daily water table fluctuations [*Osenbrück et al.*, 2009].

4.2. Age-Depth Profiles: Implications for Aquifer Recharge and Anisotropy

There is an increase in MRT with depth within the plains aquifer system, with estimated MRTs of between 1–40 years in shallow horizons increasing up to 170 years in deeper locations based on CFC-12 data and using realistic LPMs. Tracer degradation cannot be ruled out, CFC-11 degradation relative to CFC-12 is apparent (see supporting information) and this is a commonly reported issue [e.g., *Cook et al.*, 1995]; therefore, estimates based on CFC-12 should be considered as maximum potential MRTs. Given the fact that across the region postmonsoon water levels are typically less than 10 mbgl (see Figure S7), vadose zone travel times will not have a significant effect on bulk MRTs even for shallow groundwater [*Cook and Solomon*, 1995].

The widespread occurrence of anthropogenic tracers at all depths suggests that low-permeability units observed in borehole logs are not laterally continuous within the top 150 m of the aquifer system, allowing shallow groundwater to move deeper within the regional system. Samples specifically from the low-permeability horizons were not taken; therefore, low-permeability units with older groundwater ages and nested flow systems which result in zones of young and old groundwater may be present at a more localized scale [*Cardenas and Jiang*, 2010; *Gassiat et al.*, 2013]. The short MRTs and isotope data in the shallow boreholes strongly suggest that this shallow system is actively recharged by local modern meteoric sources. While recharge from the River Beas and Satluj and canal network may recharge shallow sources in close proximity to these systems [e.g., *Datta et al.*, 1996; *Sharma et al.*, 2014], stable isotope results show that groundwater recharge in this region is dominated by local areal monsoon sources.

The majority of deep boreholes show evidence of modern tracers (CFC-12 and CFC-11), only one deep site had no tracer present, and in most instances these indicate that there is a significant component of modern recharge reaching depths of at least 150 m. Using a binary mixing model, which assumes mixing between modern and tracer dead water, median and mean modern fractions were found to be 0.2 and 0.4 (i.e., 20% and 40% modern recharge, respectively) for deep sites, and $>$60% of these sites had a modern fraction of $>$0.1. The fact that significant quantities of tracer are found in deep boreholes, all of which penetrate several lower K horizons, suggests that there is a significant component of vertical leakage through lower K horizons and that they do not provide a contiguous barrier to vertical migration of groundwater in the subsurface. This is supported by sedimentary logs from this region which show that while low K horizons are prevalent within the sedimentary sequence (0–150 mbgl), they have limited lateral continuity [*Bowen*, 1985; *Singh et al.*, 2015], and this is also true for other analogous sedimentary settings in India [*Kumar et al.*, 2007; *Samadder et al.*, 2011; *Sinha et al.*, 2013]. Further work exploring the anisotropy of the aquifer system and correlations with groundwater age profiles could include an assessment of the spatial variability of the cumulative thickness of low K horizons. An alternative hypothesis for the presence of modern tracers at depth is poor borehole construction, i.e., the potential for shallow recharge to migrate vertically down the borehole annulus space, given the high standard of construction used for the deep municipal wells used in this study this is unlikely.

Using tracer data, we have also shown for the first time that areas with the greatest long-term premonsoon declines in groundwater level within the central region of the study area generally show less age-depth stratification and significant convergence in MRT at depths (ΔMRT between 0 and 0.5 yr/m, Figure 2a) of up to 150 m compared to areas that show limited long-term water level declines (Figure 2b). Local variability in the prevalence of low K horizons, as well as the level of deep abstraction, could also explain some of the spatial variability in ΔMRT. The long-term rate of groundwater decline is related to a number of factors including the distance from the Shiwalik hills, which are important recharge zones, the distance from major rivers, and, as this paper has highlighted, the influence of intensive abstraction for urban and agricultural use leading to induced recharge to the deep groundwater system in the central part of the Bist-Doab region (see Figure 2b).

Evidence from this multitracer study suggests that there is low regional hydraulic anisotropy within this part of the plains aquifer system, and in the absence of detailed 3-D lithological models, this provides an indirect assessment of the lithological controls on groundwater flow under intensive pumping conditions at depth within the aquifer. Our findings suggest that the lower *K* sequences are not likely to be regionally extensive, as is found in more distal parts of the Indo-Gangetic Basin [e.g., *Michael and Voss*, 2009], and do not provide a significant barrier to the vertical migration of recharge and potential pollutants in this part of the Indo-Gangetic alluvial aquifer system. Strong anthropogenic tracer signals in deep groundwater indicate that regional flow conditions are highly perturbed due to pumping, and may significantly enhance rapid recharge to depth, with implications for the future management of this essential resource.

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