Journal of Hydrology: Regional Studies 50 (2023) 101570

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Groundwater recharge sources and processes in northwest India: Evidence from high frequency water isotope observations

G. Krishan [a,*], D.J. Lapworth [b,*], A.M. MacDonald [c], M.S. Rao [a]

[a] National Institute of Hydrology, Roorkee, Uttarakhand, India
[b] British Geological Survey, Maclean Building, Wallingford OX10 8BB, UK
[c] British Geological Survey, Lyell Centre, Edinburgh EH14 4AP, UK

ARTICLE INFO

Keywords:
Groundwater
Recharge
Salinity
North-west India
Security

ABSTRACT

Study region: Bist-Doab, Punjab, northwest India.
Study focus: Water isotopes and specific electrical conductivity (SEC) are used in this paper to investigate groundwater recharge sources and processes in a catchment with a history of high groundwater abstraction for irrigation and canal irrigation. High frequency (every 10 days) samples for water stable isotope analysis (δ18O and δ2H) were sampled from a dense network of shallow (<50 m) and deep (>100 m) hand pumps and tube wells in Bist-Doab, northern Punjab between 2009 and 2014.
New hydrological insights for this region: The study indicates that groundwater recharge is dominated by meteoric sources from high intensity events. However, in a small proportion of sites located in close proximity to some canals and rivers have significant surface water inputs. Isotope observations indicate rapid changes in groundwater recharge sources linked to post-monsoon pumping and seasonal connectivity to surface water inputs, even at some deep sites. Rapid changes are likely linked to poor well integrity, highlighting the risk to groundwater sources from surface water ingress. Shallow groundwaters had significantly higher SEC compared to deeper groundwater observations ($p = 0.0002$). Overall groundwater SEC is still relatively low (<2000 μS/cm). However, based on previously published mean residence time of (<50 years) in shallow groundwater the high rate of change in salinity at some sites (2.5–10% per year) is of potential concern.

1. Introduction

The alluvial aquifers of northwest India are a critical water resource for sustaining crop irrigation and drinking water supplies. Both shallow and deep boreholes are used as a dominant source of water in the state of Punjab, India, and throughout northwest India (Central Ground Water Board, 2014). Surface water resources are fully utilised and most of the demands of the growing population in this region are met by groundwater (UNESCO, 2009). This can lead locally to significant decreases in groundwater levels (Hayashi et al., 2009; MacDonald et al., 2016; Van Loon et al., 2016; Wada et al., 2012; Willis and Garrod, 1998). The semi-arid terrain of Punjab, 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 and is amongst the most agriculturally productive regions of India. Understanding the processes of aquifer recharge is

* Corresponding authors.
E-mail addresses: drgopal.krishan.nihr@gov.in (G. Krishan), djla@bgs.ac.uk (D.J. Lapworth).

https://doi.org/10.1016/j.ejrh.2023.101570
Received 9 June 2023; Received in revised form 9 November 2023; Accepted 10 November 2023
Available online 14 November 2023

essential for managing this important water resource, as are assessing changes in groundwater levels and water quality (MacDonald, 2016; Lapworth et al., 2015, 2017; Krishan et al., 2021).

Stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) are commonly used in surface water groundwater interaction studies and also provide insights into water movements (e.g. Kendall and MacDonnell, 1998). They provide information on processes such as, evaporation, transpiration, recycling and mixing (Tarki et al., 2016). Recharge by direct precipitation, runoff, rivers, and reservoirs can be differentiated by their characteristic stable isotopic signatures (Krishan et al., 2021; Jasechko et al., 2013; McDonnell et al., 1990). Various other hydrologic processes that can modify the isotopic compositions in groundwater are mixing with different source waters (e.g. Lambs, 2004), enrichment in heavier isotopes owing to evapotranspiration (e.g. Bouragba et al., 2011), and isotopic fractionation during rainfall (e.g. Taylor et al., 2002).

Groundwater salinity can limit the use of groundwater for drinking water and irrigation, and high salinity has been reported across parts of southern Punjab (Krishan et al., 2021; 2022). Salinity can build up in groundwater due to a range of processes (e.g. shallow groundwater tables and waterlogging conditions due to canal leakage, flushing in of salts built up in the soil and unsaturated zone due to high evaporation) (Tweed et al., 2011; Foster et al., 2018; Li et al., 2020). While the Bist-Doab region has reported relatively low specific electrical conductivity SEC groundwaters compared to parts of southern Punjab (Krishan et al., 2021a), higher SEC has been reported in the shallow, more recently recharged groundwater compared to deeper and older parts of the aquifer (Lapworth et al., 2015, 2017). This suggests that there has been a build-up of salinity in the shallow part of the aquifer (0–50 m below ground level) due to recent anthropogenic activities over the last 3–5 decades (Lapworth et al., 2015).

The distinctive depleted isotopic signature of surface water and canal end members derived from higher altitude melt waters relative to meteoric rainfall make water isotopes an ideal tracer of groundwater provenance in northwest India (Lapworth et al., 2015; Rao et al., 2017; Joshi et al., 2018). Lapworth et al. (2015) showed that meteoric groundwater recharge sources dominated in this region of northwest Punjab based on a relatively small set of 16 paired water isotope observations in shallow and deep boreholes across the Bist-Doab region.

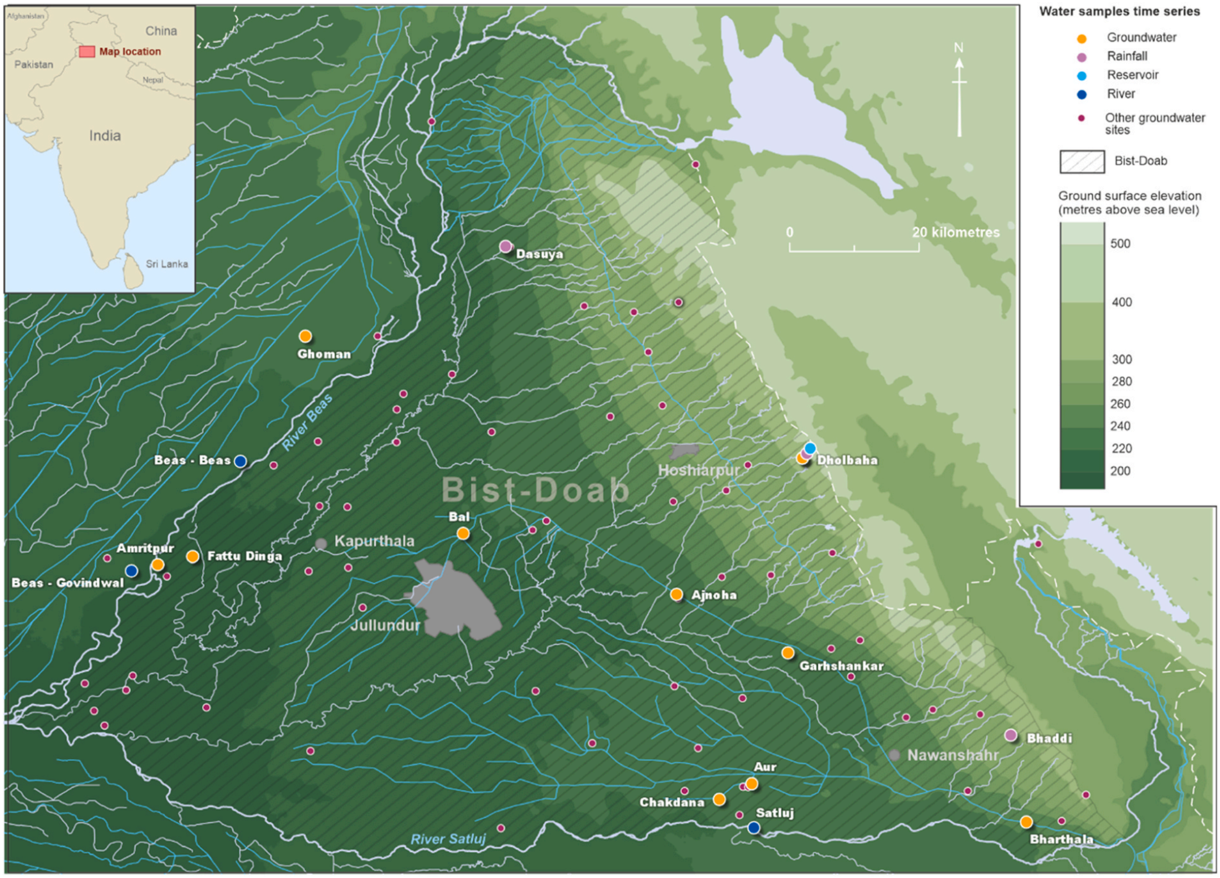

Fig. 1. Study area showing sampling points and sample types and the location of Bist-Doab in Northwest India. STRM elevation data from USGS Explorer products (90 m resolution) source: https://earthexplorer.usgs.gov/. Drainage – Digital Chart of the World (DCW) shown as white lines. Country borders, sources: Esri; Garmin International, Inc.; U.S. Central Intelligence Agency (The World Factbook). Major canal network shown as blue lines, source: from Punjab Remote Sensing Centre, Ludhiana (https://prsc.gov.in), 2008, Land Use Mapping at district and block Level on 1:50,000 scale under IMSD, NRDMS, NRIS, IT-SAP and Ministry of Agriculture (Govt. of India) sponsored projects in Punjab using IRS data. Sites with high frequency groundwater observations are shown as orange symbols, high frequency river and reservoir sites are shown as blue symbols.

This paper sets out to test if this hypothesis holds or needs to be modified based on results from a much larger water isotope data set from across the Bist-Doab. This work is highly novel in using high (10 day) frequency time series (2009–2015) for water isotope observations and salinity (2010–2015) for groundwater and high frequency isotope observations (2009–2015) from surface waters to assess groundwater recharge processes in this heavily pumped region of India. It combines the high frequency observations from selected sites across the catchment with high spatial coverage of groundwater isotopes ($n = 108$) including paired observations from 30 shallow and deep sites for water isotopes and salinity to characterise groundwater recharge sources and processes at depth within the aquifer system. The specific aims of this study are i) to use high frequency measurements to look at how groundwater dynamics and recharge sources change seasonally, ii) assess the relative importance of meteoric vs surface water (canal and river) sources of groundwater recharge, including establishing evidence for the affect of rainfall intensity on groundwater recharge in this intensively monitored study area iii) assess the vertical connectivity of the aquifer system and the impact of pumping based on paired water isotope and salinity observations within the shallow and deep parts of the aquifer system and iv) to investigate the sources for and extent of salinity build-up in the shallow part of the aquifer system using specific electrical conductivity (SEC) as a measure of salinity and stable isotope observations from across the Bist-Doab.

2. Methodology

2.1. Study area

The Bist-Doab is located between the Beas and Sutlej Rivers in Punjab, within the Indo-Gangetic plain and is characterised as having a multi-layer aquifer system (Bonsor et al., 2017). The study area covers an area of 9060 km^2, 17.6% of Punjab state, and lies between 30°51′ and 30°04′ N latitude and between 74°57′ and 76°40′ E longitude (Fig. 1). The study area is bounded by Shivalik hills in the north-east, the Beas River in the north and the River Sutlej in the south. There is a 'choe' ridden (i.e. ravine-ridden) belt in the area bordered to the north-east by the Shivalik's called the Kandi area. This area is a 'bhabhar', or a piedmont plain, lying at the foothills of the Shivalik's and formed by the coalescence of various alluvial fans resulting from the deposition of sediments by various 'choe'. The major canal network in the Bist-Doab arises from the River Sutlej. Besides these, the Kandi region is full of seasonal streams (see drainage pattern in Fig. 1). The drainage density is high in the northeast strip bordering the Shivaliks, but it is moderate to low in the rest of the area with sub-parallel and sub-dendritic patterns. The Pong dam on the River Beas feeds various hydroelectric schemes on the Mukerian Hydel Canal providing power to the region.

Temperature in summers can go up to 45 °C and normally vary between 30 and 32 °C. Winters are moderately cold with normal temperatures falling between 10 and 15 °C. Strong dry winds called 'Loo' in the summers and frost in the winters are common features of this region. Long term average rainfall (1901–2019, India Meteorological Department) in the area nearest the Shivaliks is 1200 mm/year (e.g. at Dhar Kalan) and there is a gradient of decreasing rainfall across the Bist-Doab plain (850 mm/year in Jalandhar), with high interannual and decadal scale variability.

The Bist-Doab is part of the Indo-Gangetic alluvial aquifer plain (Bonsor et al., 2017). Geomorphologically the Bist-Doab can be divided into three zones, the Shiwalik and Kandi watershed in the NE of the region, the inter-fluvial plain between the River Beas and the River Sutlej, and the floodplain areas. Thick deposits of Pleistocene to Recent sediments derived from erosion of the Himalayas and lower lying foothills have formed the deep sedimentary alluvial plain aquifer we find today (Bowen, 1985; Samadder et al., 2011; Bonsor et al., 2017).

The groundwater system of the Bist-Doab is characterised as a highly permeable aquifer system comprised almost entirely of Pleistocene-aged alluvium, consisting of medium-coarse grained sands (Bonsor et al., 2017). The Bist-Doab is typically described as having two connected aquifer units of varying thickness, the top layer of this aquifer system (typically 70–90 m thick) comprises coarse sand beds and gravels in some locations. The sand beds are generally thick and separated by thin clay beds that are not regionally extensive. The deeper aquifer extends up to 250 m below ground surface and is typically 80–100 m thick (Lapworth et al., 2015; Krishan et al., 2021a). The sediments are generally medium to coarse grained with a high permeability (K), typically–30–50 m/d but up to 50 – 70 m/d locally, and high specific yield 10 – 25% (Bonsor et al., 2017). Low permeability layers can locally stratify the aquifer, but these are rarely continuous over more than a few kilometres. Overall anisotropy (Kv/Kh) is typically < 25 in the Upper Indus; recent deposits next to the major rivers are less anisotropic. The aquifer is highly exploited with many shallow tube wells (<100 m), hand dug wells and a growing number of deeper tube wells (100 – 150 m).

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 pre-monsoon groundwater levels (Central Ground Water Board, 2011) as well as regional scale modelling studies (Cheema et al., 2014). In contrast, in some areas in close proximity to canal networks there is evidence of recharge from the leaky canal system (Kumar et al., 2011). Overall, the largest declines are found in the central plain area of Bist-Doab (Lapworth et al., 2015). The recent falls in groundwater have occurred after a century of rising groundwater levels (MacAllister et al., 2022). For more details on the regional groundwater flow and hydrogeology of this region please see Lapworth et al., (2015, 2017) and Bonsor et al. (2017).

2.2. Sampling and analysis

The water samples for groundwater (shallow <50 m depth; deep > 50 m depth), River Beas and Sutlej, Canals, Dholbaha reservoir and rainfall were all collected in 15 ml polyethylene terephthalate sample bottles, sealed, labelled and stored in refrigerated conditions. Samples were transported to National Institute of Hydrology, Roorkee for analysis. Bottles were wrapped with parafilm surrounding the bottle-caps to prevent any leakage and evaporation.

Groundwater samples were collected for between 2009 and 2014 from 108 locations; River Sutlej samples were collected from 1 location from August 2010 to February 2012; River Beas samples were collected from 2 locations 2009–2014; Canal samples were collected from 7 locations in 2009; Reservoir and rainfall samples were collected during June, 2009 to January, 2015 for isotope analysis for the parameters $\delta^{18}O$ and $\delta^{2}H$. Intensive rainwater sampling was carried out for every rainfall event from 3 sites between 2009 and 2013. Reservoir and selected groundwater and surface samples were collected every 10 days between 2009 and 2015. The sampling locations are shown in Fig. 1. Thirty paired sites in the shallow (<50 mbgl) and deeper (>50 mbgl) aquifers were used to explore depth changes in stable isotopes and SEC.

Measurements of specific electrical conductivity (SEC), 2010–2014, were carried out in the field during sampling using hand-held SEC metre (Eutech). Probes were calibrated using certified standard reference materials on a regular basis. Analysis for both of $\delta^{18}O$ and $\delta^{2}H$ was carried out using a dual inlet isotope ratio mass spectrophotometer with a precision of + 0.01‰ ($\delta^{18}O$) and 1.0‰ ($\delta^{2}H$). The isotope ratio $\delta^{18}O$ / $\delta^{16}O$ and $\delta^{2}H$ / δH were expressed in per mil units relative to Vienna Standard Mean Ocean Water (VSMOW). A bivariate plot of $\delta^{18}O$ versus $\delta^{2}H$ is used to describe the relationship among various water bodies with local meteoric water line (LMWL) (Clark and Fritz, 1997) and global meteoric water line (GMWL) of Gourcy et al. (2005).

Long-term amount weighted rainfall results were calculated for three locations (Dholbaha, Bhaddi and Dasuya) with long-term rainfall totals and paired stable isotope results. These are presented alongside the results from the different waters for comparison. Selected high frequency (10 day) groundwater and surface water stable isotope results are also presented to understand how these change over the sampling period 2009–2014. These results are presented alongside calculated weighted monthly average rainfall results over the same period.

3. Results

3.1. Variations in water stable isotope results for different water types

Table 1 summarises the water stable isotope results for the different water types investigated as part of this study (rainfall, groundwater, the two main rivers, Dholbaha reservoir and canals). Fig. 2 shows water stable isotope results as a cross-plot of $\delta^{18}O$ vs $\delta^{2}H$ for rainfall (Fig. 2a), surface waters (Fig. 2b-d) and average values for groundwaters as sample numbers vary considerably for different sites (Fig. 2e-f). Long term weighted mean rainfall (LTWMR) values for the long-term rainfall sites are shown for reference and cluster quite close together, average rainfall values across all 3 rainfall monitoring sites (1–10 mm, 11–30 mm and >30 mm) are also shown for reference as is the GMWL. The Dholbaha reservoir data clearly deviates from the GMWL, showing enrichment (more positive values) in $\delta^{2}H$ relative to $\delta^{18}O$, consistent with an evaporative mixing line ($\delta^{2}D = 5.28 \times \delta^{18}O - 10.81$, $R^2 = 0.82$, Fig. 2b). The River Beas and canal samples are isotopically depleted compared to the weighted rainfall values (Fig. 2c). The depleted end member relative to the meteoric rainfall is consistent with a higher altitude source of Himalayan water feeding the River Beas and associated canal networks. There is a small proportion of River Beas samples that show some limited evidence of evaporative enrichment (Fig. 2c). The River Sutlej data fall on a mixing line between an isotopically depleted end-member relative to meteoric rainfall where most of the data points are found, presumably again consistent with a high altitude source of water, and the meteoric rainfall (Fig. 2d). For a small number of surface water samples there is possible evidence of evaporative enrichment relative to the meteoric rainfall end-member. Groundwater samples are more consistent with the weighted rainfall values, however, both shallow (Fig. 2e) and deep (Fig. 2f) groundwater samples show a majority of data points that are isotopically depleted (more negative) relative to weighted mean rainfall and are more consistent with more depleted values found in more intense rainfall events (Fig. 2f) and fall between rainfall end members and surface water end members. There is also considerably more variability in the isotope data from the shallow groundwater relative to the deeper groundwater, consistent with the homogenisation of the meteoric isotope signatures with depth due to groundwater mixing.

Fig. 3 shows a comparison of results for shallow and deep groundwater for $\delta^{2}H$ from observations at 30 paired sites. Fig. 3a shows differences in mean $\delta^{2}H$ observed at the paired locations, error bars show 1σ around the mean where there are multiple observations. At 20 (>60%) of locations there is no significant difference between mean $\delta^{2}H$ in shallow and deep sites. Where there are significant differences in water isotopes most of these (n = 10, 80%) show enriched $\delta^{2}H$ in shallow sites compared to deeper sites (Fig. 3a). Kernel density plots of mean values from deep and shallow sites are shown for $\delta^{2}H$ (Fig. 3b). A non-parametric Wilcoxon rank sum test was

Table 1
Summary water stable isotope results for the different water sources in the Bist-Doab.

		$\delta^{18}O$-VSMOW ‰		$\delta^{2}H$-VSMOW ‰	
Water source	n	Mean	STD	Mean	STD
Rain	737	−4.09	4.84	−27.60	37.90
Shallow groundwater	1310	−6.08	1.60	−42.74	9.65
Deep groundwater	691	−6.57	1.25	−46.03	5.91
Beas River	167	−7.37	1.04	−46.76	6.55
Sutlej River	50	−8.70	3.79	−62.39	27.47
Dholbaha Reservoir	133	−3.50	1.31	−29.26	7.63
Canals	9	−9.12	1.88	−62.02	12.31

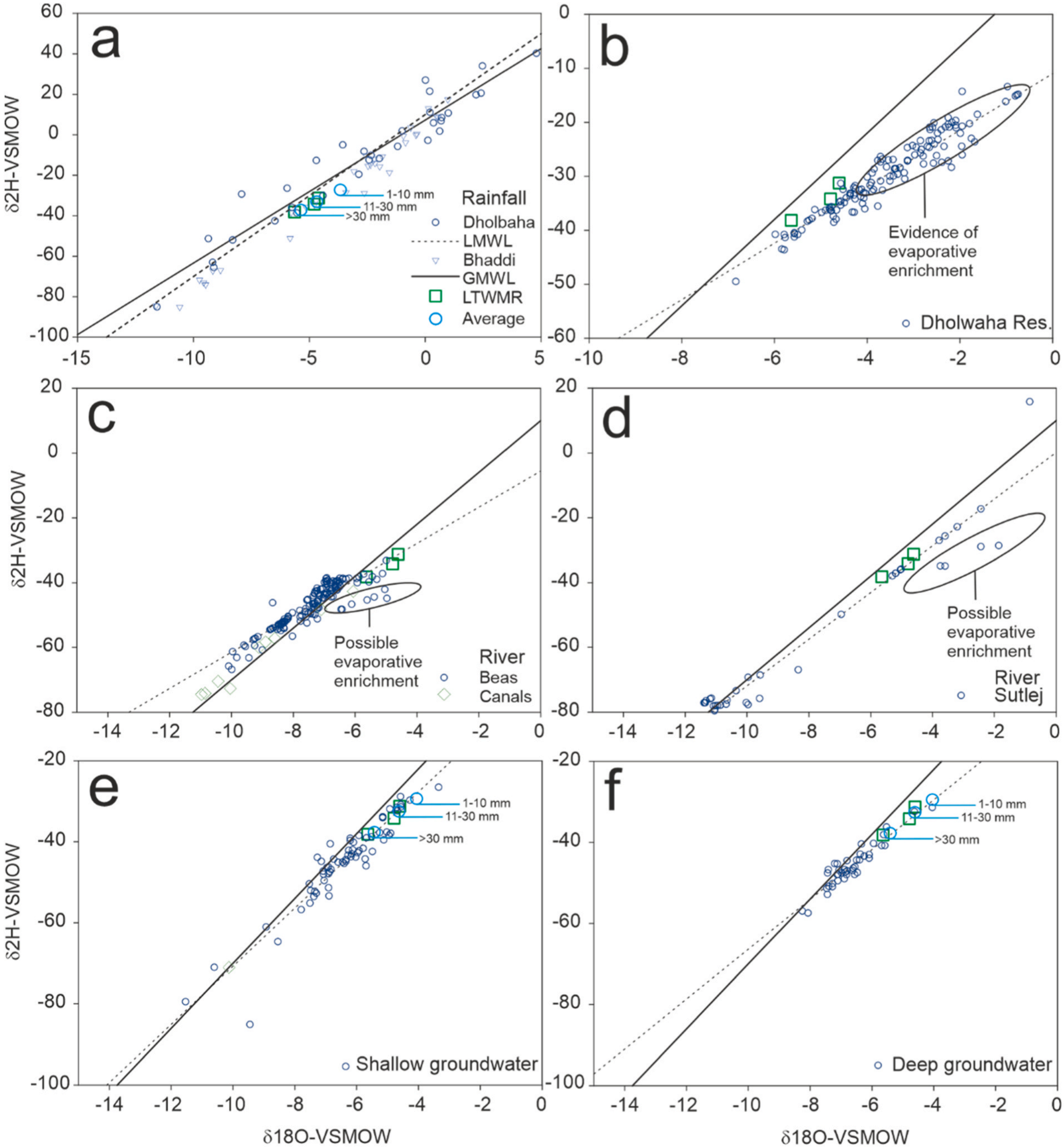

Fig. 2. Cross-plots of $\delta^{18}O$ vs $\delta^{2}H$ for a) monthly amount weighted rainfall, b) Dholbaha reservoir, c) River Beas and canals, d) River Sutlej, e) average shallow groundwater observations and f) average deep groundwater observations. Solid line is the GMWL for each plot, the dashed line is the LMWL for plot(a) or a regression line through the data points for plots (b-d). Long Term amount Weighted Mean Rainfall (LTWMR) for three rainfall stations in the Bist Doab (Dholbaha, Bhaddi and Dasuya) are shown as open square symbols for reference. Symbol size is comparable with measurement error for $\delta^{2}H$ VSMOW, the precision of $\delta^{18}O$ +/- 0.01‰. Large blue symbols show average stable isotope values for rainfall binned by rainfall amount (1–10 mm, 11–30 mm and >30 mm).

used to test if these two samples (deep vs shallow) were from the same population for $\delta^{2}H$. Samples were significantly different at the 0.05 level and not from the same population ($p = 0.04$).

3.2. Variations in SEC with depth for groundwaters

Fig. 4 shows a comparison of results for shallow and deep groundwater for SEC from observations at 30 paired sites. Fig. 4a shows

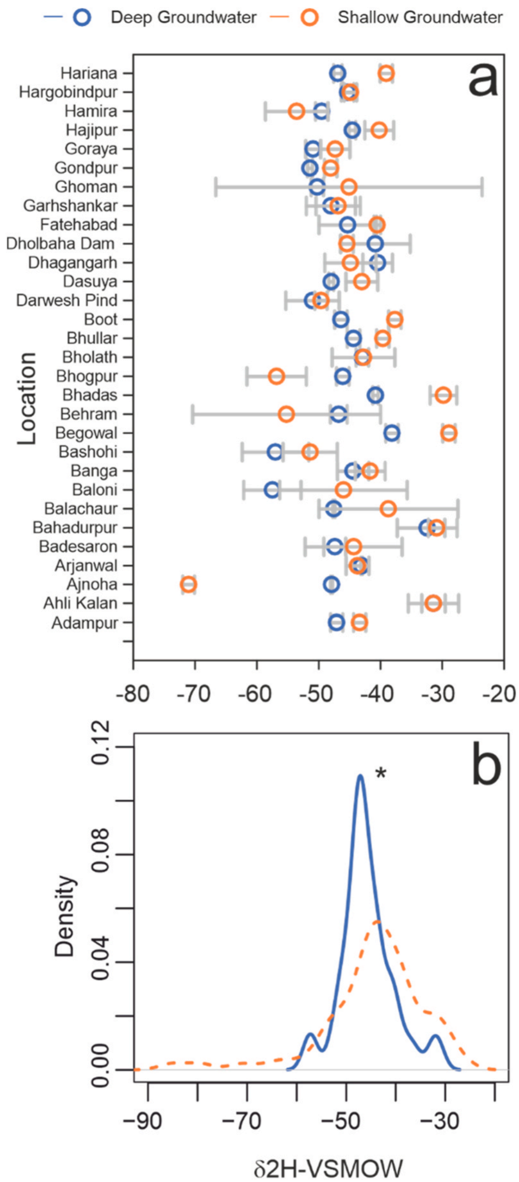

Fig. 3. δ^2H VSMOW measurements in groundwater for paired shallow and deep sites a) Mean δ^2H VSMOW, b) δ^2H-VSMOW kernel density plots. Error bars indicate 1σ around the mean for plot (a). * (b) indicates statistically significant difference between samples, $p = 0.04$, using a Wilcoxon rank sum test.

differences in mean SEC observed at the paired locations, error bars show 1σ around the mean where there are multiple observations. On a site basis there are significant differences in mean SEC observed at ($n = 13$, 43%) of locations, and at nearly all locations ($n = 28$, 93%) mean shallow groundwater SEC was higher than deep groundwater SEC. The two sites that show the reverse trend of higher SEC in deeper groundwater are Fatehabad and Gondpur, however differences in mean SEC are only significant for Fatehabad. Kernel density plots of mean values from deep and shallow sites are shown for SEC (Fig. 4b). A non-parametric Wilcoxon rank sum test was used to test if these two samples (deep vs shallow) were from the same population for SEC. Samples were found to be significantly different at the 0.001 level and not from the same population ($p = 0.0002$).

3.3. Time series of stable isotope results for groundwater and surface waters

High frequency time-series for δ^2H measurements in shallow and deep groundwater between 2009 and 2015 from six locations are shown in Fig. 5. Amount weighted monthly mean rainfall δ^2H values from data collected at the Bhaddi rainfall station are shown for comparison. Horizontal lines show average water isotope values for groundwaters, and shaded area in the plot show where the monsoon dominates in this region. Rainfall values are enriched relative to groundwater values, particularly during the 'non-monsoon'

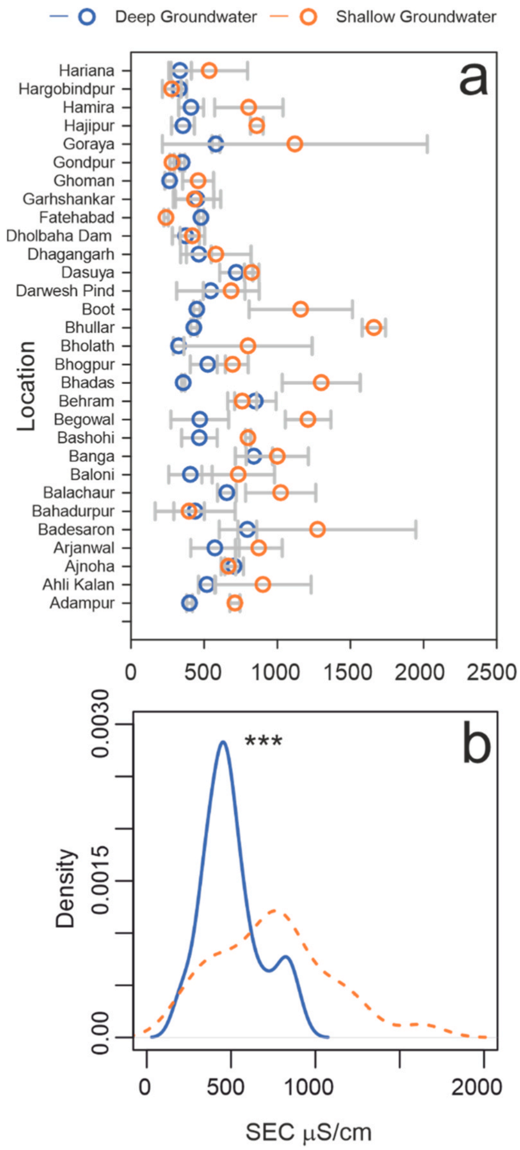

Fig. 4. SEC measurements in groundwater for paired shallow and deep sites a) SEC mS/cm, b) SEC kernel density plot. Error bars indicate 1σ around the mean in plot (a). *** (b) indicates statistically significant difference between samples, p = 0.0002, using a Wilcoxon rank sum tests between deep and shallow observations.

period, with a repeated pattern of depletion in rainfall δ^2H during the progression of the monsoon (Fig. 5). For 5 of the 6 time-series the stable isotope composition of the deep and shallow groundwaters are significantly different for the majority of measurements. However, all groundwater time-series show a high degree of variability, with notable enrichment in δ^2H coinciding with the end of the monsoon on a regular basis. At 2 of the 6 sites (Dholbaha and Ghoman, Fig. 5a and f) the deep groundwater is more enriched compared to the shallow groundwater for most of the time, at 2 sites (Fattu Dhinga and Aur Fig. 5b and e) the reverse is true and shallow observations are more enriched compared to deep sites. At one site (Garhshankar, Fig. 5d) deep and shallow observations are comparable throughout the monitoring period and at one site (Amritpur Fig. 5c) deep groundwater observations start more enriched (more positive) compared to shallow observations early on in the monitoring (2011) and then become more depleted relative to shallow observations as the timeseries progresses (2012–2015). These site-specific trends reflect the range of depth variations observed for the larger number of sites shown in Fig. 3.

High frequency time-series for δ^2H are shown for two monitoring stations (Beas and Goindwal) on the River Beas (Fig. 6a) one site on the River Sutlej (Fig. 6b) and the Dholbaha Reservoir (Fig. 6c). The results for the Beas (Fig. 6a) show comparable results from both monitoring stations ($\rho = 0.65$, $p = 0.0009$, spearman's rank correlation) and an overall increase in δ^2H during the monitoring period (2010–2015), with a more pronounced seasonal variation during the first two monsoons. There is more limited data for the River Sutlej (Fig. 6b) collected between 2010 and 2012, this too shows quite large seasonal changes with more depleted values towards the end of

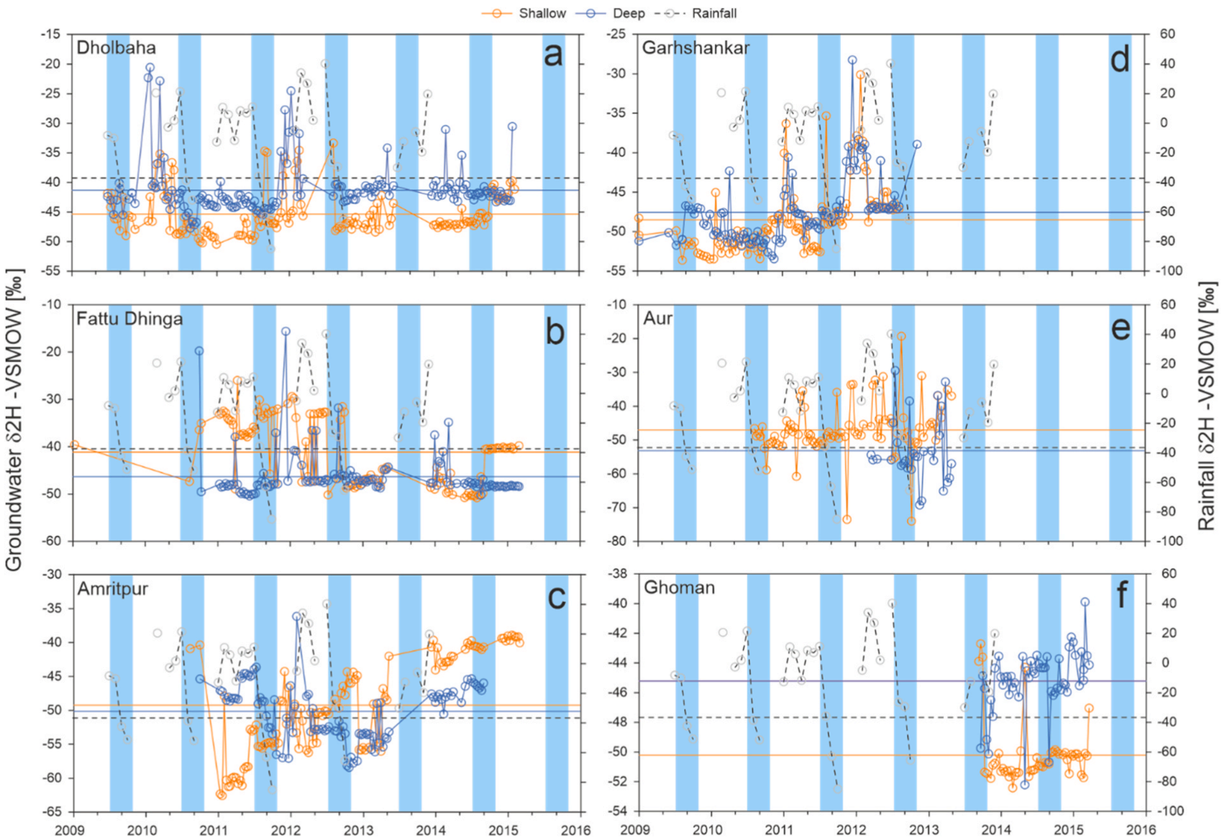

Fig. 5. High frequency δ^2H VSMOW time series for paired deep and shallow groundwaters a) Dholbaha, b) Fattu Dhinga, c) Amritpur, d) Garhshankar, e) Aur and f) Ghoman. Amount weighted monthly average data shown in black symbols for Dholbaha rainfall as reference. Blue bands indicate the monsoon period in this part of India. See Fig. 1 for the location of monitoring points within the Bist-Doab. Black dashed line shows the amount weighted rainfall values for Dholbaha. Measurement precision is equivalent to the symbol size in the plots.

the monsoon and significantly more enriched values observed during the non-monsoon periods. The Dholbaha reservoir time-series was collected between 2009 and 2015 and has a similar cyclical pattern with enriched δ^2H during non-monsoon periods and increasingly depleted δ^2H observations during the progression of the monsoon which follows patterns seen at the other surface water sites and also for rainfall (Fig. 6). The cyclical pattern is not clear in the latter half of the monitoring period (2013–2015) which mirrors the results for the River Beas and rainfall during this period.

Groundwater SEC timeseries are shown in Fig. 7 for selected sites within the Bist-Doab which have longer records and also overlap with site the high frequency stable isotope timeseries shown in Fig. 5. Given the short length of the observations and high variability at some sites fitted linear trends are only indicative. Three sites show increases in SEC in shallow groundwaters over the period of observation (Fattu Dhinga c.15 μs/cm/y, Amritpur c.15 μs/cm/y and Ghoman c.50 μs/cm/y), one site shows decreases (Garhshankar c.40 μs/cm/y). However, the timeseries is only for two years and one site (Dholbaha) shows no clear trends. For 3 sites the trends in shallow boreholes are matched in deep boreholes, while at Ghoman and Amritpur there are no trends in the deep boreholes over the short period of observations.

4. Discussion

4.1. *Relative importance of meteoric vs surface water recharge sources in groundwater*

A significantly larger (c. 4 times the number of sites) groundwater isotope data set than has been previously used (e.g. Lapworth et al., 2015) has been assembled to revisit the question of the provenance of the groundwater in the shallow and deep part of the aquifer system in the Bist-Doab. When average groundwater isotope values for shallow and deep groundwater sites are compared with amount weighted rainfall values and surface water end-members this new data set confirms the overall dominance of meteoric sources of groundwater recharge (see Fig. 2). However, it is interesting to note that the majority of groundwater sites do show a small depletion in δ^2H relative to the meteoric amount weighted rainfall values which is consistent with a small contribution of surface water recharge. A significant localised deviation away from the amount weighted rainfall value for the rainfall recharge end-member is possible but unlikely given the consistent monsoon rainfall patterns observed in this area (Fig. 5) and the similar amount weighted rainfall values

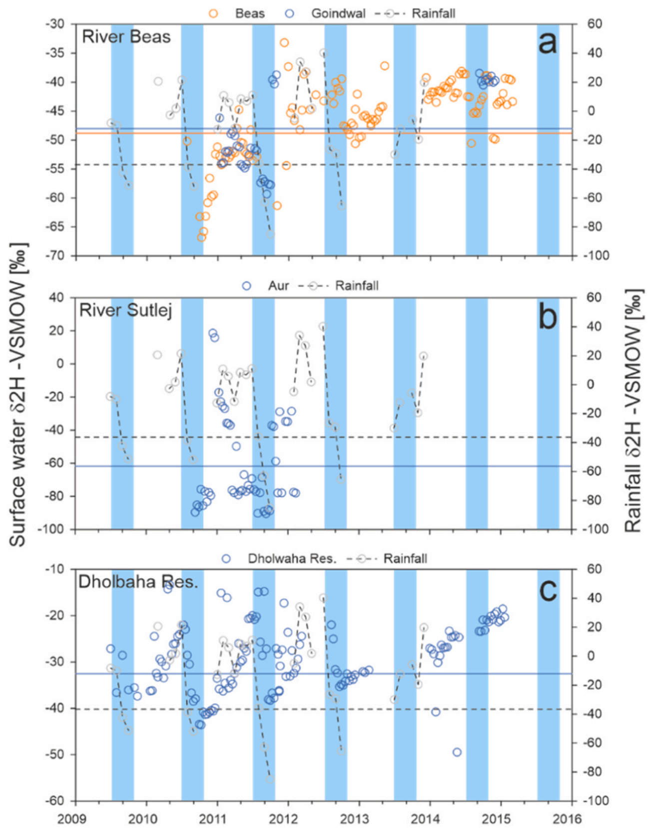

Fig. 6. High frequency δ^2H VSMOW time series for surface waters in Bist Doab a) River Beas at two locations, b) River Sutlej and c) Dholbaha Dam. Amount weighted monthly average data shown in black symbols for rainfall as reference. Blue bands indicate the monsoon period in this part of India. Black dashed line shows the amount weighted rainfall values for Dholbaha.

found in this study. A small proportion of surface water samples show evidence of enrichment due to evaporative effects (Fig. 2c and d). However average water isotope values for groundwaters do not show any evidence of evaporative enrichment relative to the GMWL or LMWL (Fig. 2e and f).

Using a simple two end member mixing approach (with an average canal and depleted River Sutlej value of −70 δ^2H VSMOW ‰ making up one end-member and the average amount weighted rainfall value of −35 δ^2H VSMOW ‰ the other end-member) more than 70% of the shallow groundwater sites have more than 60% contribution from meteoric sources. In contrast, less than 10% of sites have a surface water contribution exceeding 20%. Shallow groundwater monitoring locations which appear to show a high proportion of surface water recharge based on this approach include Bal, Bharthala, Ajnoha, Garhashankar and Chakdana, all of which are in very close proximity to surface water sources (Fig. 1). It is likely that a combination of groundwater pumping at these sites and seasonal flow from the surface waters towards adjacent alluvial aquifers due to changes in river stage enhances surface water contributions at these locations (Lu et al., 2022). Due to the more limited spread of data for deeper sites (Fig. 2f) % contributions from surface water sources at depth are much lower as would be expected but are still evident at some sites.

Groundwater stable isotope time-series and pairwise comparisons show that there are significant differences between deep and shallow groundwater isotope signatures at the same locations (see Figs. 3 and 5). However, water isotope values are more consistent with those observed for meteoric rainfall, particularly from more intense rainfall events, rather than surface water sources at all depths. However the spread of more depleted average groundwater isotope values which fall between rainfall and surface water end-members does strongly suggest that at some sites canal and river ingress is important. The significantly depleted deeper water isotope values ($p = 0.004$) for δ^2H (and δ^{18}O) compared to shallow groundwaters suggests that there has been a small but significant long-term shift in the groundwater isotope values over the last 40–170 years, towards more enriched isotope values, based on published groundwater residence time data (Lapworth et al., 2015). This could be due to the significant development of groundwater pumping during this period in this region (MacAllister et al., 2022). This difference could also be due to the reduced influence of canal leakage in recent decades (Keesari et al., 2017) or could be due to the preservation of a much older meteoric/climate signal in the deeper groundwaters as a result of more focussed historical recharge occurring at the break in slope between the Shiwalik-Kandi hills and the plains (Fig. 1). The anisotropy of the alluvial aquifer and low gradients in the floodplain under limited pumping influence (historically) would have resulted in the formation of groundwater age stratification with depth, with much older groundwaters in the mid plain and at discharge boundaries of the Bist-Doab. Groundwater residence time tracers (tritium and CFC and SF6) from deeper wells in this region supports

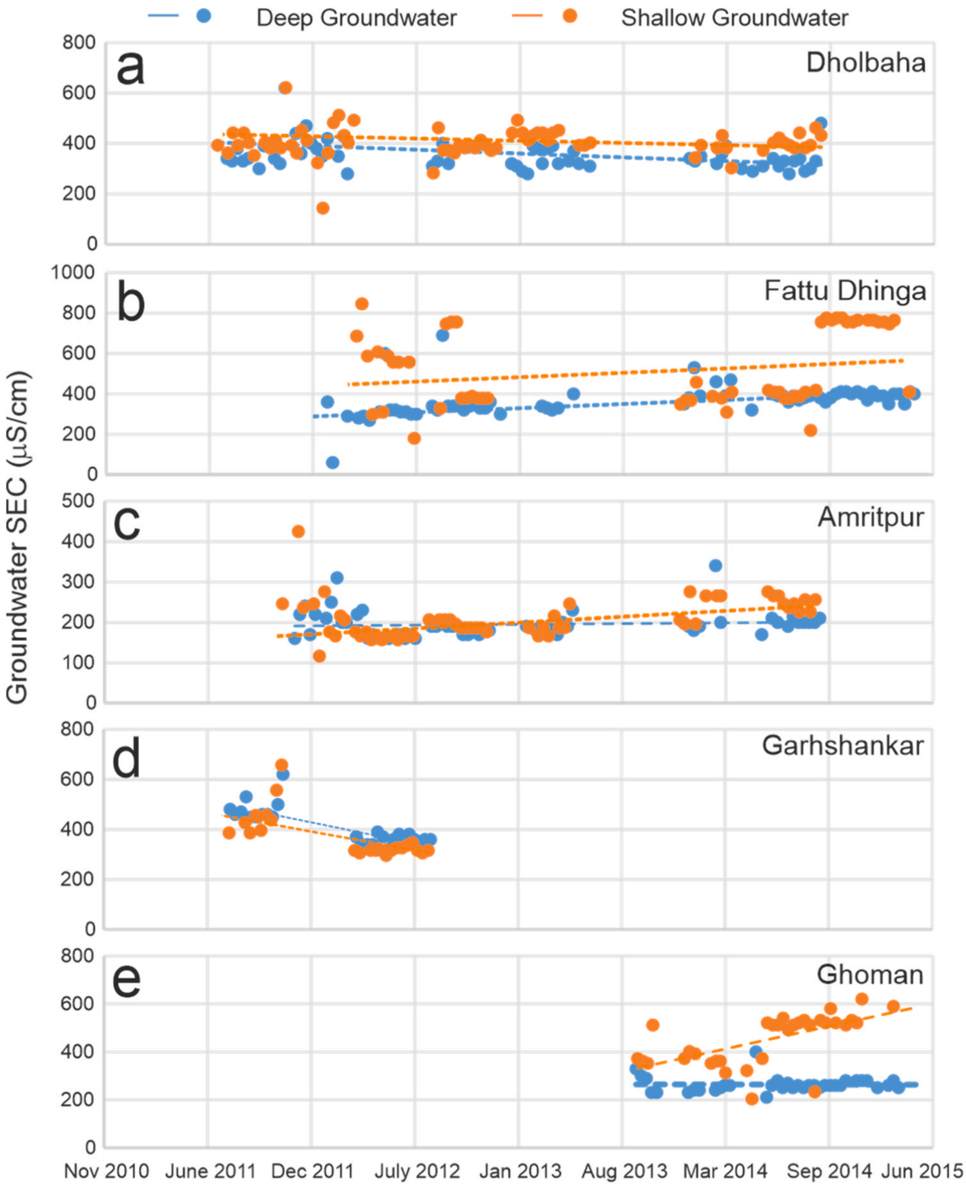

Fig. 7. High frequency SEC groundwater time series a) Dholbaha, b) Fattu Dhinga, c) Amritpur, d) Garhshankar, e) Ghoman. Lines show linear fits through the data. Given the short length of the data series and variability trends are only indicative.

this hypothesis of much older recharge sources at depth (Lapworth et al., 2015; Krishan et al., 2021a) although there is now an overprint of ingress of more modern recharge at depth due to canal leakage and localised pumping affects (Lapworth et al., 2017; Keesari et al., 2017). The shift to more depleted signatures with depth is also consistent with the hypothesis that recharge in the past was more dominated by episodic flooding (e.g. period between 1800 and 1850 has been shown to have been historically particularly wet), with river flow from intense rainfall events generated at higher altitudes in the Himalayas, which would have a more depleted isotopic signature (Kathayat et al., 2022). Shallow water isotope values from Ajnoha (see Fig. 3b) are shown to be highly depleted and are an outlier from the rest of the data set of 29 pairwise observations and this is likely due to a significant contribution from surface water sources at this site due to its proximity to a canal.

4.2. Impact of seasonal pumping on the ingress of shallow groundwater sources to depth

While the time series data for water isotopes in groundwater show significant differences between shallow and deep observations for the majority of the monitoring period, there are noticeable regular deviations in the timeseries away from ‘average’ conditions at all sites and these changes are seen simultaneously in both shallow and deep sites (Fig. 5). These deviations from average conditions typically show relatively enriched δ^2H values for groundwaters and the majority coincide with non-monsoon periods. During these times it is noteworthy that both shallow and deep samples show significant enrichment towards rainfall values (Fig. 5). The timing of these observations coincides with the period of enhanced groundwater pumping in northwest India due to reduced monsoon rainfall and sustained irrigation demands for crops (Bhatt, 2021). It is therefore most likely that this simultaneous change in isotope value in water samples in both deep and shallow sites is driven by changes in borehole pumping regimes that take place across the Bist-Doab and elsewhere in northern India. This suggests that the pumping is drawing in shallow sources of recharge which temporarily shift the water stable isotope values of groundwater samples collected towards a broader range of rainfall values typical of this period (see Fig. 5). This shift to more enriched water isotope values rules out canals and rivers as the main source of recharge during these periods (Fig. 2) and suggests that the recent pumping is capturing a broader range of recharge events and not just those from higher intensity events (i.e. >30 mm) (Fig. 2a).

Given that these isotope signals are transitory and rapidly return to 'pre-pumping/monsoon' conditions it is thought that these are localised borehole scale effects caused by either anulus flow due to high vertical gradients set up by intense pumping at depth in the high permeability strata (Lapworth et al., 2015; Krishan et al., 2021a).

For the majority of sites with long-term timeseries data no significant long-term trends are evident (Fig. 5). However, one site (Amritpur, Fig. 5c) does show a shift towards more enriched water isotope values with time, with a clear upward trajectory between 2013 and 2015 for both shallow and deep groundwaters. This is mirrored in the upward SEC trend at this site over the same period (Fig. 7). This points to a larger scale shift in the groundwater recharge source at this site, possibly due to more extended/permanent changes in pumping regimes during the monitoring period which is drawing down higher SEC recharge water to depth within the aquifer. At another site (Garhshankar, Fig. 5d) the values and trends for water isotopes are comparable for both the deep and shallow sites, while there is a downward trend for SEC for both shallow and deep sites (Fig. 7), suggesting that these may represent surface water inputs which are susceptible to rapid pumping induced changes in water isotopes and SEC. There is clearly no evidence of depth stratification at this location which is untypical of most paired observations (Figs. 3 and 6). This is also supported by the near identical SEC values at the two depths at Garhshankar (see Fig. 4). This could be due to the absence of a low permeability horizon at this location separating the two parts of the aquifer system (Lapworth et al., 2015; Shekhar et al., 2020) or perhaps there has been a longer history of pumping at this location which has induced significant vertical recharge and mixing of groundwater to depth within the aquifer system.

4.3. Evolution of shallow and deep groundwater salinity and implications of salt accumulation at a regional scale

There is a statistically significant increase in SEC at shallow sites compared to deep sites for the 30 paired observations used in this study ($p = 0.0002$, Fig. 4). Average SEC values for shallow sites are 750 μS/cm, 50% higher than values in deeper sites which have an average SEC of 500 μs/cm. This trend is also supported by local scale observations of Groundwater SEC timeseries which show increases in shallow groundwaters at selected sites over short timeframes (Fig. 7). There is no evidence of widespread evaporative enrichment water stable isotopes based on average site data (Fig. 2e, f) so this an unlikely significant contributing factor to shallow groundwater SEC. The net shift in shallow sites to more enriched water isotope values (Fig. 3) is also not consistent with a global shift towards greater surface water inputs, SEC would typically be lower in most surface water sources (e.g. rivers and canals) compared to groundwater. The effects of waterlogging due to shallow groundwater levels seen across large parts of the rest of the Indus Basin is not the main driver in this setting either due to higher rate of groundwater abstraction and lower groundwater levels in this region (Sidhu et al., 2020). The shift in SEC could be due to flushing of salts accumulated in the soil due to evaporation by rains at the start of the monsoon, or perhaps the use of more salty groundwater for irrigation where fresh groundwater is not available (Xiao et al., 2015; Foster et al., 2018).

Assuming that the deeper groundwaters represent conditions which largely predate the agricultural revolution in India, which is a fair assumption as the mean residence times for groundwaters at depth (>50 mbgl) are between 40 and 170 years and have lower nitrate concentrations (Lapworth et al., 2015, 2017), the most likely reason for the shift in shallow groundwater SEC over this period is due to enhanced diffuse anthropogenic inputs of salinity to shallow soils and groundwater over the last 5 decades (Lapworth et al., 2017; Coyte et al., 2019; Foster et al., 2018; Krishan et al., 2020). Shallow groundwater ages were found to be between 5 and 20 years (Lapworth et al., 2015), with an average increase of SEC of 50% on this basis it represents a rapid average rate of salinity increase of between 2.5% and 10% per year in shallow groundwater. This is also mirrored through short term groundwater SEC time series observations at selected sites (Fig. 7). This could include inputs of both organic and inorganic fertilisers to maintain crop yields, which has greatly increased over this timescale as multiple crop cycles have become the norm across the region sustained by groundwater pumping over the same period (Krishan et al., 2021a). High groundwater nitrate concentrations have been observed in this region in shallow groundwaters and do point to the role of fertiliser inputs (Lapworth et al., 2017). Salt inputs will also include inputs from urban and industrial activities, including waste-water inputs, which has likewise intensified hugely over this timeframe in the Punjab region as the population has increased (Krishan et al., 2021b) as well as the flushing in of salt that has built up in the soil during the non-monsoon (Foster et al., 2018). While absolute SEC values in shallow groundwater are still relatively low compared to WHO drinking water guidelines for example (WHO, 2011), the high rate of change seen at selected sites and the significant difference between the shallow and deep groundwaters is of concern and suggests that the current salt inputs to groundwater may not sustainable at current rates in the medium-long term.

5. Conclusions

Through a comparison of average groundwater isotope values for shallow and deep groundwater sites with amount weighted rainfall values and surface water end-members this new data set confirms the overall dominance of meteoric sources of groundwater recharge. Using a simple two end member mixing approach (between local surface water and rainfall) more than 70% of the shallow groundwater sites have more than 60% contribution from meteoric sources.

The significantly depleted deeper water isotope values ($p = 0.004$) for δ^2H compared to shallow groundwaters suggests that there has been a small but significant long-term shift in the shallow groundwater isotope values over the last 40–170 years (based on groundwater residence time data from Lapworth et al., 2015). This could be due to a number of processes; changes in the influence of canal leakage with time and the role of enhance capture of meteoric sources (with a broader range of isotope signatures) due to pumping, the preservation of a much older meteoric/climate signal at depth and; the fact that recharge in the past was more dominated by episodic flooding.

While the high frequency time series data for water isotopes in groundwater show significant differences between shallow and deep observations for the majority of the monitoring period, there are noticeable regular deviations in the timeseries away from 'average' conditions at all sites and depths. These changes are seen simultaneously in both shallow and deep sites. The timing of these observations coincides with the period of enhanced groundwater pumping in northwest India due to reduced monsoon rainfall and sustained irrigation demands for crops (e.g. Shekhar et al., 2020) and is likely caused by pumping promoting the ingress of groundwater capture during this period.

There is a statistically significant higher SEC at shallow sites compared to deep sites for the 30 paired observations used in this study ($p = 0.0002$, Fig. 4). Average SEC values for shallow sites are 750 μS/cm, 50% higher than values in deeper sites which have an average SEC of 500 μs/cm. The shift in SEC could be due to flushing of salts accumulated in the soil due to evaporation by unenriched water at the start of the monsoon, or perhaps the use of more salty groundwater for irrigation where fresh groundwater is not available. While absolute SEC values in shallow groundwater are still relatively low compared to international guidelines, the high rate of change is of concern and suggests that the current salt inputs to groundwater are not sustainable at current rates in the medium-long term.

CRediT authorship contribution statement

G. Krishan: Conceptualization, Investigation, Data curation, Writing – review & editing. **D.J. Lapworth:** Conceptualization, Data curation, Investigation, Methodology, Writing - original draft, Writing - review & editing. **A.M. MacDonald:** Conceptualization, Writing – review & editing, Funding. **M.S. Rao:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The study was carried out under PDS (HP-2), project during 2009–13, BGS-DFID project during 2013–15. The data analysis and validation of samples work were carried out under BGS, UK sponsored project. DL and AM were also funded under TerraFIRMA: Future Impacts, Risks and Mitigation Actions in a changing Earth system is funded by the UKRI natural Environment Research Council, grant reference NE/W004895/1 and the BGS International NC programme 'Geoscience to tackle Global Environmental Challenges'. We thank Donald John MacAllister for undertaking an internal review of this paper prior to submission.

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