Intensive Groundwater Exploitation in the Punjab – an Evaluation of Resource and Quality Trends

Groundwater Science Programme

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D J Lapworth, K Gopal, M S Rao, A M MacDonald

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Groundwater resilience, intensive pumping, groundwater residence times, groundwater quality.

Front cover

Irrigated wheat fields in Bist-Doab, Punjab, India (DJ Lapworth).

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Foreword

This report is an output from the project *Groundwater resilience to climate change and abstraction in the Indo-Gangetic basin*

Groundwater resilience to climate change and abstraction in the Indo-Gangetic basin is a two-year (2012-14) research project strengthening the evidence-base linking groundwater resources, climate variability and abstraction in the Indo-Gangetic basin. This project has been funded by UK aid from the UK Government, and led by the British Geological Survey, however the views expressed do not necessarily reflect the UK Government's official policies. The project has two main aims:

- To develop a strategic overview assessment of the occurrence and status of groundwater resources in the Indo-Gangetic basin and develop a map of groundwater typologies spanning the groundwater system
- To strengthen the evidence-base linking groundwater resources, climate and abstraction through a series of four targeted case studies in the basin.

The project team involves researchers from the British Geological Survey, IIT Kharagpur, ISET-Nepal, ISET International, Meta-Meta, National Institute of Hydrology (Roorkee), Overseas Development Institute, University College London, University of Dhaka and Bangladesh Water Development Board.

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Summary

This report summarises initial findings from a case study investigating the response of groundwater resources in Punjab State, India, to irrigated agriculture. Punjab was central to India’s green revolution, and with fertile soils, abundant surface water and groundwater resources, Indian’s farmers soon transformed the State to be the “bread basket” of India. Currently approximately 20% and 11% respectively of India’s wheat and rice production, 10% of cotton production comes from Punjab.

The aim of the case study is to examine the response of groundwater in a representative area within Punjab to current pressures from sustained intensive abstraction and pollution, investigate groundwater recharge, and forecast likely future trajectories. The Bist-Doab area was chosen as for the case study: the geology and hydrogeology is typical of the Punjab, situated on the thick and extensive multi-layered alluvial Indo-Gangetic aquifer and has an annual average rainfall of 700 mm. The Doab is one of the most productive agricultural regions in the Punjab and has experienced intense groundwater pumping from shallow aquifers for at least the last four decades. The hydrogeology of this region is best understood as an aquifer system comprising a series of thick high permeability horizons (>10 m thick) divided by thick low permeability horizons with highly variable lateral extent. Locally these are referred to as the first (shallow), second and third etc. (deep) aquifers, although the aquifers are not laterally continuous over long distrances.

The following work was undertaken from 2013 to 2014:

An analysis of groundwater level monitoring data (1970-2012) from the Indian Central Ground Water Board (CGWB) was carried out.

New hydrochemical observations and residence time indicators (CFC and SF_6) taken from 19 locations were obtained from paired shallow (<50 mbgl) and deep (>100 mbgl) sites across the Bist-Doab under pre and post monsoon conditions. Stable isotope observations were collected and assessed within the context of an ongoing study by NIH investigating spatial and temporal changes in stable isotope chemistry in groundwater and surface water across Bist-Doab.

Long-term groundwater monitoring undertaken by the CGWB since the 1970s shows declining shallow pre-monsoon groundwater levels (up to 0.8 m/y in places) across 20-25% of the Bist-Doab. Hydrographs responses imply that for some areas this has led to enhanced recharge during the monsoon. However, for the most affected region of the Bist-Doab, declining *post* monsoon water levels suggest that abstraction for irrigation is now outstripping the enhanced recharge potential. In the long-term this will lead to a continued decline in shallow groundwater levels pre-monsoon, currently commonly found to be >20 mbgl, with future implications for irrigation.

For most sites there is a significant difference between stable isotope values for the paired deep and the shallow groundwater, with deeper sites showing isotopically depleted signatures relative to the shallow samples. This is consistent with different recharge areas and pathways for the paired sites at any given location, with the deeper sites have a greater component of water that was recharged some distance up-gradient (i.e. towards the recharge zone at the foot of the Shiwalik range). This source has a depleted isotope signature compared to the shallow aquifer due to Raleigh distillation processes as monsoon moisture tracks from the Bay of Bengal. Based on the distinct depleted stable isotope values of the Sutlej canal system, there is no evidence of significant component of regional groundwater recharge in either the shallow or deeper aquifer from this source. However, it is likely that this is important at locations in close proximity to the canal network.

Results obtained using chlorofluorocarbon (CFC-12) groundwater age tracers show that average shallow groundwater mean residence times (MRTs) are 29 years and 30 years under post-monsoon and pre-monsoon conditions. Deep groundwater (>100 mbgl) had median MRTs of 45

years. There is no obvious relationship between deep groundwater MRTs and distance from the recharge zone at the foot of the Shiwalik hills. However, deep groundwater MRTs are much younger than would be expected under natural groundwater flow regimes, where groundwater residence times of the order of ca.10^2-10^3 years or more might be expected based on the aquifer properties and the distance from the recharge zone, some 50- 100 km down-gradient in many cases.

Areas with fastest long-term declining groundwater levels show evidence of enhanced modern recharge in both shallow and deep groundwater, suggesting that there is a significant component of vertical leakage to deeper aquifers induced by long-term intensive pumping. This corroborates findings from modelling studies undertaken in analogous multi-layered alluvial systems in Gujerat, India (Rushton 1986).

There is evidence of nitrate breakthrough from the shallow groundwater to depth and this is likely to be enhanced in the future if the current increases in pumping from the shallow and deep aquifers continue. This has implications for future contamination of deep sources of drinking water from other anthropogenic contaminants such as pesticides.

The naturally occurring contaminants arsenic and fluoride were present at concentrations below WHO guideline drinking water limits for all sites and median concentrations were below 2 μg/L and 0.4 mg/L respectively. Uranium concentrations in deep groundwater are significantly higher compared to shallow groundwater ($p<0.05$), with median values >15 μg/L, the provisional WHO guideline concentration for drinking water is currently 30 μg/L (WHO, 2012). This is a result of water-rock interactions and mineral dissolution and longer residence times.

The findings from this case study have broad relevance across a large geographical area as similar groundwater typologies extend within the Indus basin, to the west across Indian Punjab, Rajasthan and Pakisan Punjab as well as in the Ganga basin to the east in the Indian states of Haryana and Delhi. While the broad findings from this study are relevant across a large geographical area, local anthropogenic and geogenic factors, as well as heterogeneity, will of course influence the recharge, hydraulic flow processes and geochemistry, and need to be considered in a consistent way.

1 Introduction

Groundwater is a critical resource for millions of people in the Punjab who rely on it for drinking water, agriculture and industry. Overall, the Punjab region is highly dependent on groundwater (Garduno et al., 2011; Wada et al., 2010; 2012).

The mid plains region of NW India is one key area for food production where groundwater levels have been reportedly dropping over a sustained period of time due to intense abstraction (Wada et al., 2012). While groundwater levels are falling in some parts of Punjab, evidence from modelling work suggesting that groundwater recharge in this region is actually increasing (Döll, 2009) and may continue to do so for some time, with pressures from intensive pumping the two processes are not mutually exclusive. Modelling studies undertaken in India suggest that pumping may actually induce post monsoon recharge in some parts of the IGB (e.g. Chaturvedi and Srivastava, 1979). Understanding the connectivity of the shallow and deep aquifers is important for assessing both the vulnerability of the deep aquifers to the migration of contamination to depth and understanding sources of recharge in the deeper aquifers. Using environmental tracers, such as chlorofluorocarbons (CFCs) and isotopes, is one key way to explore connectivity and anisotropy in this aquifer system.

This report outlines preliminary findings from a case study focussed on understanding the response of groundwater resources to sustained abstraction for irrigation in Punjab State. The aim of the case study is to examine the response of groundwater in a representative Doab to current pressures from abstraction and pollution and forecast likely future trajectories. Specific objectives were:

- To collate historical water level responses to abstraction across the catchment
- To collate new evidence on recharge processes, groundwater quality, groundwater residence times, and connectivity of the layered aquifer systems and surface water by repeated sampling of shallow and deep piezometers using a suite of environmental tracers
- To obtain new high frequency data on water level variations in shallow and deep piezometers for one hydrological year

1.1 BACKGROUND – PUNJAB AND THE GREEN REVOLUTION

Punjab means the land of five Rivers: the River Jhelum, Chenab, Ravi, Satluj and Beas, and all are tributaries of the Indus River. The Indian part of Punjab is divided into four geographic regions: Malwa (region south of river Satluj), Bist Doab (region between the rivers Satluj and Beas), Majha (region west of river Beas) and Powadh (region in Rupnagar and Ambala district) that falls between the Rivers Satluj and Ghaggar.

Punjab state is one of the most productive agricultural regions in India. This is a semi-arid region with annual average precipitation of ca. 700 mm. The agricultural activity of the state is reliant on a dense network of canals, with a total length of 14,500 km that distributes water from the Rivers Satluj, Ravi and Beas as well as the extensive use of groundwater extraction for irrigation (approx. 33 BCM per year (Punjab Remote Sensing Centre, 2008) through millions of its state and private owned pumps. From the 1960s an era of sharp agricultural growth in Punjab was sustained partly through intensive irrigation. The state has become synonymous with the 'Green [agricultural] Revolution' which was sustained in part though the intensive growth in groundwater irrigation. This boom in the agricultural sector earned Punjab the accolade of the 'bread basket of India' due to its spectacular growth in wheat and rice production. Punjab is the highest per capita electricity consuming state in the country. The agricultural dominance of the state can be seen from the fact that the state produces 19.5 % of India's wheat, 11% of India's rice and 10.26 % of India’s cotton. In 2013 the state’s NPK fertilizer consumption was 470 kg per hectare of sown area compared to 54 kg nationally (Statistical Abstract, Punjab, 2013; Indian Department of Fertilizers 2014).

Table 1 summarises the changes in cropping patterns for Punjab between the 1970 and 2012. This shows that agricultural output in the state has grown significantly since the adoption of modern techniques in the late 1960s (Sidhu, 2005). Important crops for the state include rice, sugarcane, fruits and vegetables. Industries in the state include the manufacture of scientific instruments, electrical goods, financial services, machine tools, textiles, sewing machines, sports goods, starch, tourism, fertilizers, bicycle, garments and the processing of pine oil and sugar. Most of the Punjab is an alluvial plain, bounded by mountains to the north.

Table 1. Cropping patterns in Punjab (Area in ‘000 ha)

Crop	**1970-71**	**1980-81**	**1990-91**	**1999-2000**	**2000-01**	**2011-2012**
Rice	390 (6.9)	1183 (17.5)	2015 (26.9)	2604 (33.2)	2612 (32.9)	2826(35.8)
Maize	555 (9.77)	304 (4.50)	183 (2.44)	163 (2.08)	164 (2.07)	133 (1.69)
Bajra & Jowar	212 (3.73)	70 (1.03)	12 (0.16)	5 (0.06)	6 (0.08)	2.5 (0.03)
Groundnut	174 (3.06)	83 (7.23)	11 (0.15)	5 (0.06)	4 (0.05)	2.0
Cotton (American)	212 (3.73)	502 (7.42)	637 (8.49)	381 (4.86)	358 (4.51)	482.8 (6.25)
Sesame	15 (0.26)	17 (0.25)	18 (0.24)	145 (1.85)	19 (0.24)	5
Sugarcane	128 (2.25)	71 (1.05)	101 (1.35)	108 (1.38)	121 (1.52)	70 (0.89)
Kharif Pulses	33 (0.58)	58 (<0.86)	73 (0.97)	51 (0.65)	42 (0.53)	-
Wheat	2299 (40)	2812 (41)	3273 (43)	3388 (43)	3408 (42)	3510 (44)
Barley	57 (1)	65 (0.96)	37 (0.49)	51 (0.65)	32 (0.40)	11.7 (0.15)
Gram	358 (6.3)	258 (3.81)	60 (0.8)	6 (0.08)	8 (0.1)	2.2 (0.03)
Rapeseed & Mustard	103 (1.81)	136 (2.01)	69 (0.92)	56 (0.71)	55 (0.69)	-
Potato	17 (0.30)	40 (0.59)	23 (0.31)	76.0–(1)	64 (0.81)	64 (0.81)
Other Vegetable	23 (0.41)	24 (0.36)	31 (0.41)	47 (0.6)	46 (0.58)	-
Fruits	50 (0.88)	29 (0.43)	69 (0.92)	30 (0.38)	34 (0.43)	71.5
Net Sown Area	4053	4191	4218	4243	4264	4158
Total Cropped Area	5678	6763	7502	7847	7935	7882
Cropping Intensity	140	161	178	185	186	190

Source: Statistical Abstract of Punjab, 1971, 1981, 2000, 2001, 2010. Area for each crop is shown in units of ‘000ha with figures in parentheses indicate area under crops as percentage share to total cropped area. Cropping intensity is total cropped areas (single+double+triple)/net cropped area * 100.

1.2 GROUNDWATER AND IRRIGATION IN THE PUNJAB

The network of canals, some of which are more than 150 years old, have steadily reduced in their carrying capacity due to siltation and leakage and decreased the availability of surface water across the region. The net-area irrigated by canals has decreased from 55% in 1960-61 to 29% in 2006-07. The canal irrigation system irrigated about 1.3 million hectare of land in 1970-71, while only one million hectare was irrigated during 1999-2000. In contrast, tube well irrigation, particularly in the central and northern region of Punjab, has increased from 55% in 1970 to 75% in 2001-02 (Punjab Remote Sensing Centre, 2008) (Figure 1). In the state of Punjab the level of groundwater use is estimated to exceed replenishable groundwater resources by a factor of 1.4, the highest level of overuse of any state in India (Gandhi and Namboodiri 2002).

Today there are an estimated 1.1 million tube wells in the state abstracting water for agricultural irrigation and another estimated 150 thousand in urban and semi urban areas to provide water for domestic and industrial purposes.

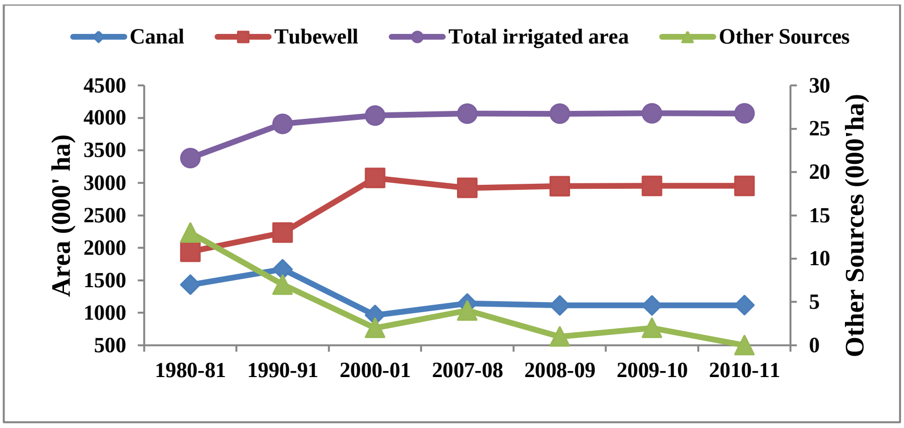


Figure 1. Comparison of net irrigated area (‘000 ha) by different sources in Punjab (Source: Statistical Abstract of Punjab, 2013)

Long-term downward trends in parts of the mid Plains Aquifer in Punjab (NW India), in the headwaters of the Indus, suggest that the current pumping regime is not sustainable, and will likely impact the poorest parts of the community which cannot afford to deepen boreholes (Chawla et al., 2010; Fishman et al., 2011). The intensive farming carried out in this region largely relies on pumping from the shallow aquifer (0-50 m) and uses large quantities of fertilisers and chemicals to control pests and sustain yields (Chaudhary et al., 2000; Kuldip-singh et al., 2013). In responds to the groundwater security issues in Punjab a number of initiatives are being implemented by the state government for improving water use efficiency, these include:

- Propagation of irrigation water saving techniques, for example laser grading of fields, zero tillage and directly seeded rice
- Rainwater harvesting and recharge structures are being constructed in the sub-mountainous region
- A subsidy of up to 85% on micro-irrigation, a 50% subsidy on underground pipeline systems to individual farmers, 90% subsidy for the community underground pipeline projects
- Watershed management projects are being implemented in 26 locations

The rapid expansion of urban centres in NW India has also contributed to the anthropogenic contaminant loading in the shallow aquifers of the Plains (Purushothaman et al., 2012; Singh, 1994). As such, the shallow aquifers in this region are polluted, both microbiologically and chemically, and are not reliable sources of drinking water. To mitigate this problem there have been large programmes across groundwater dependant states such as Punjab to install deeper boreholes (ca. 150 m) to supply groundwater for drinking water in urban and peri-urban settings which requires minimal treatment. How sustainable this is in the long-term depends on the nature and degree of contamination in the shallow subsurface, as well as the vertical variation in the hydraulic properties and geochemical conditions within the layered sedimentary aquifer system.

There is currently a limited understanding of the degree of confinement in the deeper aquifers and their sources of recharge. A better understanding of the vertical age profiles and water quality variations within the layered sedimentary aquifer is needed to inform and support a thorough assessment of the vulnerability of the deeper aquifers to i) the downward migration of contaminants from shallow sources and ii) the mobilisation of natural sources of contamination at depth due to changing redox conditions.

2 Case study area

2.1 GEOGRAPHY AND CLIMATE

The Bist-Doab covers an area of 9060 km^2. The word "Doab" signifies the region between two rivers (here the Satluj and Beas). Groundwater levels are shallow in the confluence region with some associated salinity issues. Bist-Doab comprises the Nawanshahr, Hoshiarpur, Kapurthala and Jalandhar districts of Punjab State, India. It is bounded by Siwalik range in the north-east, the river Beas in the north and west sides and the river Satluj in south and east-south. The area lies between 30°51'N and 30"04'N latitude and 74"57'E and 76"40'E longitude (Figure 2). The study area is part of the Indo-Gangetic alluvial aquifer plain. The drainage density is high in the NE strip bordering the Siwalik hills, but it is moderate to low in the rest of the area with sub-parallel and sub-dendritic patterns. In the plain area the gradients are low, with a regional gradient of around 0.4 m/km towards the SE.

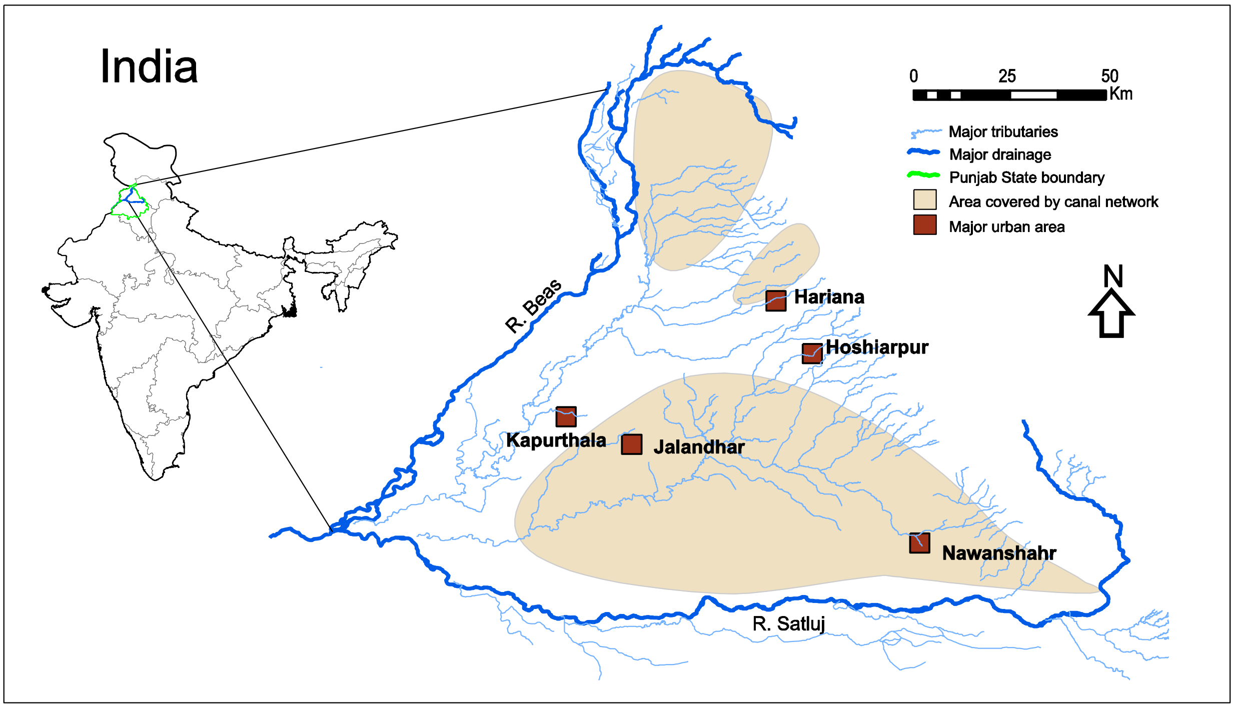


Figure 2. Location of Bist-Doab (ca.9000 km^2) major drainage, canal network coverage and urban centres

The Beas and Satluj rise in the high Himalayas and traverse long distances in the Himalayan and Siwalik zone before entering the state of Punjab. The Bist Doab area is comprised of a low hilly area locally known as the Kandi region, and the central plains. In the Kandi region, north-east portions of Hoshiapur and Nawanshehar, there are deeper groundwater tables, due to the change in topography, and this region is traditionally considered the recharge area for the deeper plain aquifer system. Some parts of Nawanshahr and Jalandhar districts are irrigated using canals from the Satluj, however, most of the area of Bist-Doab is irrigated using shallow groundwater (ca.90%). The 'shallow' boreholes abstract from aquifers that are normally at least 10m thick and no deeper than 50 meters below ground level. 'Deep' boreholes abstract from aquifers that are for the most part >100 meters below ground level and are also >10m thick.

The drainage density is high in the NE strip bordering the Siwalik hills, where there are regular parallel channels cutting through the Shiwalik range which drain on to the plain. Drainage density is moderate to low in the rest of the area with sub-parallel and sub-dendritic patterns. In the plain area the gradients are low, with a regional gradient of around 0.4 m/km towards the SE (Bowen, 1985).

The climate of the Bist-Doab is semi-arid and there is a moderate temperature and rainfall gradient SE-NW across the Bist-Doab region. There is annual average rainfall of ca. 700 mm in Jalandhar, in the middle of the catchment, the greatest rainfall occurs between mid-June and September. Temperatures in the lower plain area range between 25-48 °C in the summer (May) and between 5-19 °C winter months. Slightly higher annual average rainfall occurs to the NE of the Bist-Doab region in the Shiwalik hills (ca. 900 mm/a) where temperatures are also generally lower, however the seasonal variations in rainfall and temperature are similar to other parts of the Doab.

2.2 GEOLOGY

The Bist-Doab is part of the Indo-Gangetic alluvial aquifer plain. This is described in detail in Bowen (1985) and Khan (1984), and summarised below. Geomophologically the Bist-Doab can be divided into three zones, the Shiwalik and Kandi watershed, the interfluvial plain between the R. Beas and the R. 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. The major lithologies and sequences in order of increasing age and depth comprise:

- Quaternary surface deposits
- Holocene Sirowal sediments and occasional gravels with inter-bedded course clastics from the Kandi belt and red clay beds to the southwest
- Pleistocene boulder beds and inter-bedded clays: Boulder conglomerate (Middle Pleistocene); Pinjore Psammite/Arenites with calcareous/ferruginous cements (late Pliocene)

Plate 1. Holocene Sirowal sedimentary deposits in the North of the catchment

The polymictic nature of the sediments reveals their heterogeneous provenance resulting from an influx of sediment from a number of sources draining the Himalayas (Bowen, 1985). The sources are pre-Cenozoic and Palaeogene/Neogene or Cenozoic crystalline and sedimentary rocks in the vicinity of Shimla, identified through fragments of parent rock in the Pinjore beds. The infilling of the basin demonstrates that the rate of uplift and erosion was outstripped by the rate of deposition through the Holocene and Pleistocene. Fill, scour and bedding structures indicate a predominantly southward flow direction during this period (Bowen, 1985). Calcrete deposits, referred to in India as *Kankar*, are extensively developed within the sediments deposited in the Bist-Doab inter-fluvial area. This deposit is composed of calcium carbonate and has a nodular form in this region and is deposited as a result of upward capillary action in arid/semi-arid conditions and as a result of leaching minerals from shallow soil horizons. These can form low permeability horizons and are also important in controlling soil and groundwater pH and geochemical processes.

2.3 HYDROGEOLOGY

In the Kandi region, north-east portions of Hoshiapur and Nawanshehar, there are deeper groundwater levels, due to the change in topography, and this region is traditionally considered the recharge area for the deeper plain aquifer system. The transition from the Kandi belt to the plains and sudden change in slope results in a dense network of drainage that recharges the plain aquifers. Figure 3 shows a simple schematic cross-section with a regional conceptual model of groundwater flow and recharge processes. Zone 1 has higher rainfall (900 mm/y) and higher areal and surface water recharge, zone 2 has lower rainfall (700 mm/y) and recharge from irrigation and seepage from canals and zone 3 has lower rainfall (600 mm/y), shallow groundwater and limited recharge potential. Some parts of Nawanshahr and Jalandhar districts are irrigated using canals from the R. Satluj, however, most of the area of Bist-Doab is irrigated using shallow (0-50 m) groundwater (>90% groundwater irrigation). Historically rising water levels, waterlogging and related salinity issues was a problem in the southwestern part of the Bist-Doab, and as the groundwater in this region is fresh groundwater pumping was encouraged to lower water tables and improve agricultural productivity.

The alluvial aquifer system comprises a series of layered aquifers of with higher porosity of sand and gravel deposits which are separated vertically by low permeability aquitards comprised of thick clay horizons as well thick *Kankar* deposits of $CaCO_3$. The aquifers and aquitards are highly variable both in terms of thickness and areal extent. Details from borehole logs in Bowen (1985) show that aquifers have horizons that are typically >20 m thick and are separated by clay and kankar horizons between 3-50 m thick. A N-S transect of logs in Bowen (1985) from Khudda (N) to Mioonwal (S) shows that aquifer and aquitard horizons are spatially highly variable. There are however regions of apparent continuity, although it must be noted that there are relatively few logs available, for example, between Njka (N) and Dhisian (S), covering a distance of ca. 50 km, there appears to be a consistently thick (ca. 15 m) clay horizon between the upper aquifer (<15 mbgl) and the second aquifer (ca 30-50 mbgl).

There is also clear evidence that paleochannels cut across low K horizons providing vertical connectivity and are important in controlling hydrogeolocial processes within the Indo-Gangetic plains (Samadder et al., 2011). This setting is considered comparable lithologically to locations further south in Gujurat reported by Phadtare (1985) and referred to by Rushton (1987). However, there is still limited evidence on the lateral extent of low K horizons and high K horizons or aquifers. Regionally, it is perhaps best described as an aquifer system which can be conceptualised as a series of aquifers with varying degrees of anisotropy but with overall higher horizontal (K_h) compared to vertical (K_v) hydraulic conductivity. The degree of anisotropy (K_h/ K_v) can be as high as 10^2-10^4 in alluvial systems when significant clay layers are present (Michael and Voss, 2009; Sinha 2009).

Early hydrogeological studies in this region focussed on understanding areal groundwater recharge using tritium tracers (Datta and Goel, 1977; Goel and Datta, 1977). Recharge studies carried out in at 7 sites across the Bist-Doab in 1972 (Datta and Goel, 1977) using tritium tagging gave average recharge (from irrigation and rainfall) values of 93 ±60 mm for the monsoon period between June and November. The data set showed a bimodal distribution with one cluster of sites with average recharge values of 35 ±3 mm and a second cluster with much higher average recharge of 136 ±35 mm, with low recharge values located close to floodplain regions and the higher values in the plains region.

There is limited aquifer property data for transmissivity (*T*) and storage coefficients (*S*) in the study area, a summary of values are presented in Bowen (1985). However, there is a paucity of data and so estimates of *T* and *S* must be treated with caution, quoted values for transmissivity range from 1700-5180 m^2d^{-1} from shallow aquifers across the catchment. Storage coefficients in the Kandi and Shiwaliks range from 0.0013-0.004 and from the plain region higher values have been estimated between 0.082-0.31.

Although it is beyond the scope of this report, the quarterly long-term water level monitoring data could be used to estimate the spatial variation of recharge, provided certain assumptions regarding the effects of abstraction (and storage) on water levels hold true. Our high frequency monitoring data collected at 6 sites shall be critical in validating the applicability of this technique with low frequency data.

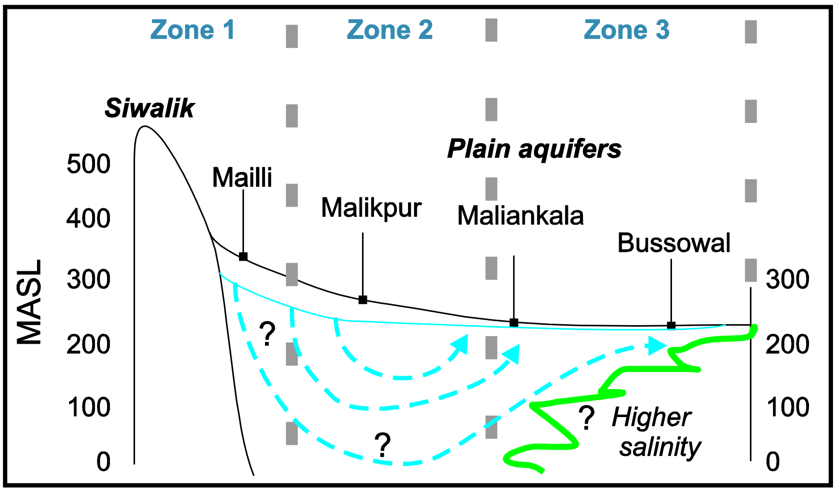


Figure 3. Simplified schematic cross section of post monsoon regional groundwater flow (distance from the edge of the Shiwalik range to Bussowal is ca. 100 km)

2.4 GROUNDWATER QUALITY ISSUES FROM PREVIOUS STUDIES

In Ludhiana, to the south of Bist-Doab, the shallow aquifer is contaminated with cyanide and chromium from industrial waste sources (Singh, 1982). More recent studies have largely focussed on groundwater quality assessments for irrigation (Kuldip-singh et al., 2013; Kuldip-Singh et al., 2011; Purushothaman et al., 2012) and used GIS approaches to map the potential of artificial recharge in the area to augment natural recharge (Singh et al., 2013; Singh et al., 2010). Dhillon and Dhillon (2003) investigated the links between elevated soil selenium (Se) concentrations and Se occurrence in shallow groundwaters in part of the Bist-Doab region. Future climate change scenarios point to an increases in high intensity rainfall during monsoon months, but overall lower soil moisture in NW India, increasing the potential for microbial contamination of shallow groundwaters (Nicholls et al., 2012; Parry et al., 2007). Lower soil moisture levels may also reduce the potential for soil denitrification and therefore a greater potential for nitrate leaching to groundwater (Groffman and Tiedje, 1989; Ruser et al., 2006).

3 Methodology

3.1 LONG-TERM CHANGES IN GROUNDWATER LEVEL

As part of this case study, historical groundwater level data (1975-2012) for the Bist-Doab was obtained from the CGWB groundwater monitoring database. Sites with groundwater level data in Bist-Doab are shown in Figure 4, some of the large urban centres in the catchment are also shown for reference. A total of 123 sites (yellow sites in Figure 4) had water level records, however only 43 (green sites in Figure 4) of these had long-term records, i.e. >20 years, with useful frequency. Most long-term monitoring sites have 4 water level records each year, taken as manual dips in May, August November and January, to capture the pre-Monsoon and post Monsoon changes in groundwater level across the catchment.

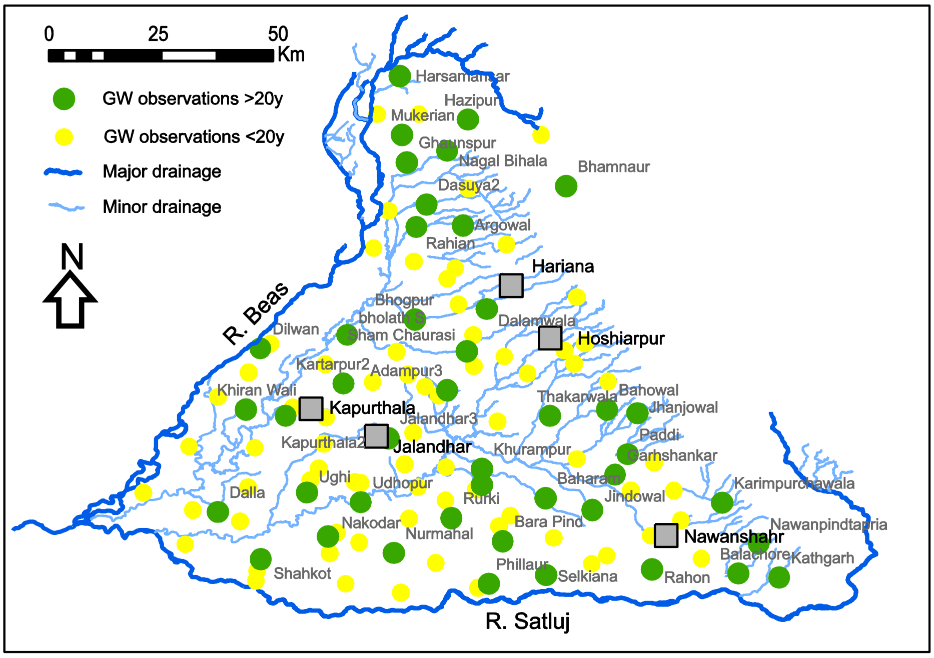


Figure 4. CGWB groundwater level records in Bist-Doab, grey squares show selected urban centres (source: CGWB)

A preliminary analysis of three key components of the groundwater level data was undertaken for the long-term monitoring sites: i) the degree of groundwater level decline, ii) the minimum groundwater level under pre monsoon conditions and iii) the nature of long-term post monsoon recovery in groundwater level.

The level of decline, pre monsoon depth and recovery during monsoon were mapped across the catchment to investigate spatial variations in groundwater resources and long-term security for shallow abstraction.

3.2 ENVIRONMENTAL TRACERS

Chemical properties of groundwater can be used as environmental tracers and so enable conclusions to be drawn about the water's origin, residence time and hydrogeochemical evolution. In addition to stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) major elements (e.g. NO_3, Mg/Ca) and trace elements (e.g. Sr, Li, Rb, Mo), which are common in many hydrogeological investigations (e.g. Edmunds et al., 2003), two specialised tracer techniques have been used in this study: Chlorofluorocarbons (CFCs) and SF_6 trace gases. Additional samples for noble gas analysis were also taken to obtain recharge temperatures, these results will not be discussed in this report as analysis is as yet incomplete.

3.2.1 Stable Isotopes

Stable O and H isotopes are tracers of physical processes that water molecules undergo between evaporation from the ocean and arrival in the aquifer via recharge of rainfall (Clark and Fritz 1997). They are typically used in semi-arid hydrogeological studies to indicate the degree to which waters may have been modified prior to recharge or the existence of pre-Holocene waters. In addition, stable isotopes and other conservative anions such as Cl and Br can be used as field tracers when applied to the surface. A small pilot study using this method to estimate recharge velocities in the shallow unsaturated zone was carried out as part of this study, however the analysis for these samples is not complete and the results from this work will not be covered in this report.

3.2.2 Trace gas age indicators

The use of CFCs and SF_6 as groundwater age tracers relies on the rise in their atmospheric concentrations over the last 50 years together with certain assumptions about atmospheric mixing and recharge solubility (Plummer and Busenberg 1999). These gases are known to be well-mixed in the atmosphere so the curves are considered to be applicable to the study area. The use of several trace gases is recommended as under certain conditions individual tracers may have limitations (Darling et al. 2012). In particular, the CFCs may be affected by pollution, and/or degradation under anaerobic conditions (Plummer and Busenberg 1999), and there are also issues with the use of SF_6 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. An average annual air temperature of 26°C was used for this study to represent recharge temperatures. The phenomenon of ‘excess air’ incorporated during recharge has only a small effect on the CFCs but requires correction for SF_6 measurement. Significant numbers of deeper sites in the pre-monsoon sampling round showed enriched SF_6 concentrations, greater than 10 times modern concentrations, suggesting terragenic sources of SF_6 in groundwaters. In addition, due to the elevated temperatures in the region (45-50 °C) during the sampling, a number of SF_6 samples expanded and broke the glass bottles and/or lids rendering the samples unsuitable for dating. In light of both of these factors only the CFC data is presented in this report.

Lumped parameter models (LPM) typically used to describe some of the variation seen in groundwater mixtures include piston flow (PFM), exponential mixing (EMM) and binary mixing (BMM) (Zuber 1986; Cook and Böhlke 2000). With the absence of SF_6 data with which to assess groundwater flow processes, for this report two simple mixing models have been used to compare results from different sites across the catchment: i) a binary mixing model (assuming mixing between modern and CFC dead water) to estimate fraction of modern recharge and ii) a simple PFM has been used to estimate mean residence times (MRT) of groundwater samples.

3.3 GROUNDWATER SAMPLING

Shallow (approx. <50 m) and a deep (generally >80m) groundwater was sampled from 19 paired sites (see Figure. 5 and Table 2) across the catchment. These were selected to ensure a good geographical spread across the catchment, and to ensure that the three main hydrological setting in the catchment were coved adequately, namely i) the upper NE portion of the catchment within the lower Shiwalik range, ii) the centre of the Doab including areas with known groundwater depletion, ii) locations in close proximity to both the R. Beas and Satluj and at the lower end of the catchment near the confluence of the two Rivers. Only sites which had good borehole completion were selected to minimise localised sources of contamination, and the distance between the shallow and deep sites at each location was minimised. Shallow sites were <50 mbgl, with the exception of one site at Ajnoha, and deep sites were >100 mbgl. Although there were differences in completion depths between locations and shallow sites were all completed in the first sedimentary aquifer, and where records were available, deep sites were shown to be completed in the second or third aquifer. This term ‘aquifer’ refers to a continuous layer of permeable sediment >10 m thick. The aquifers are separated by low permeability clay, silt and *kankar* deposits.

Groundwater was sampled using existing hand pumps and tube wells during February and May, 2013 for pre-monsoon season and during October, 2013 for post monsoon sampling. The sample locations were recorded using Global Positioning System (GPS). Prior to sampling, boreholes were purged (minimum 3 borehole volumes) to ensure a fresh sample was collected. Groundwater chemistry was monitored carefully for a range of field parameters including electrical conductivity (EC), pH, redox potential (Eh), dissolved oxygen and temperature using a flow-through cell. Only after stable field readings were obtained were samples collected. Field alkalinity was determined by titration in the field using 50 ml sample and 1.6 N sulphuric acid.

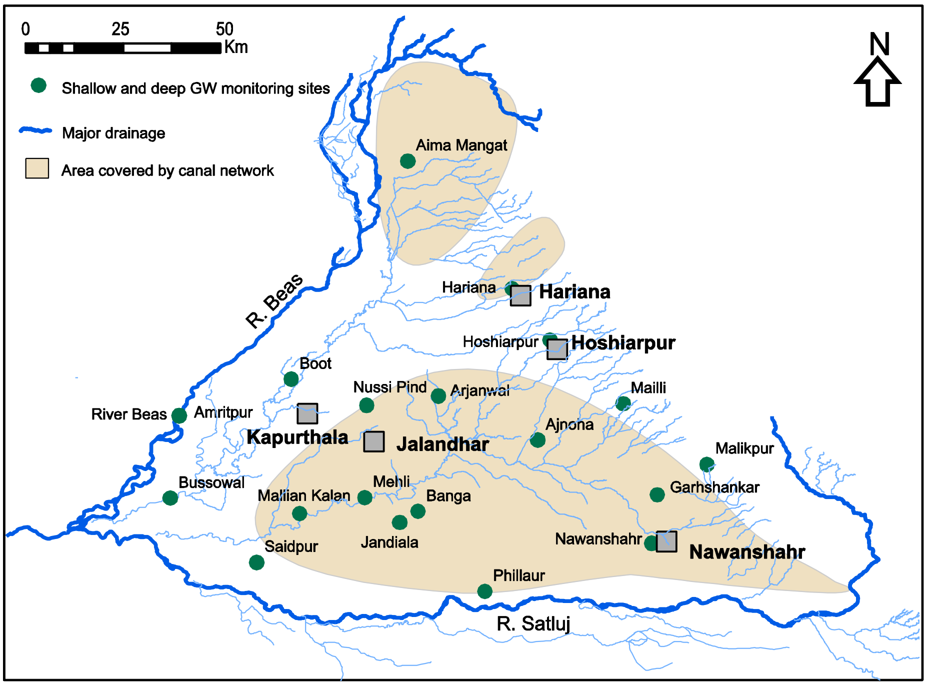


Figure 5. Location of paired shallow and deep monitoring sites across the Bist-Doab

Table 2. Sampling site names, locations, districts and completion details

Site Name	District	Longitude (E)	Latitude (N)	Depth (m) Shallow	Depth (m) Deep
Banga	Nawanshahr	75.5°9'36.4"	31°10'04.4"	16	100
Mehli	Nawanshahr	75.4°8'51.4"	31°12'47.6"	40	150
Phillaur	Jalandhar	75.4°47'26.2"	31°01'24.1"	30	80
Malikpur	Phagwara	75.4°50'07.5"	31°16'55.6"	25	160
Nawanshahr	Nawanshahr	76°07'11.5"	31°07'33.1"	30	130
Maili	Hoshiarpur	76°04'12.7"	31°24'07.3"	45	80
Hariana	Hoshiarpur	76°50'29.6"	31°38'06.2"	50	160

Aima Mangat	Hoshiarpur	75°37'57.6"	31°53'32.5"	20	85
Arjanwal	Jalandhar	75°41'44.2"	31°25'13.5"	10	140
Jandiala	Jalandhar	75°37'07.8"	31°09'46.4"	30	60
Saidpur	Jalandhar	75°19'43"	31°05'06.1"	35	122
Mallian K.	Jalandhar	75°24'57.1"	31°10'57.4"	35	130
Busowal	Kapurthala	75°09'17.5"	31°12'49.2"	9	130
Boot	Kapurthala	75°23'52.1"	31°27'11.6"	10	130
Garhsankar	Hoshiarpur	76°08'07.8"	31°13'34"	18.3	45.7
Hoshiarpur	Hoshiarpur	75°55'09"	31°31'55.4"	45.7	64
Ajnoha	Hoshiarpur	75°53'46.4"	31°19'36"	67	121.9
Nussi Pind	Jalandhar	75°33'2.5"	31°24'02"	21.3	152.4
Amritpur	Kapurthala	75°10'21.8"	31°22'49.5"	7.6	76.2

Filtered (0.45µm, cellulose nitrate) water samples were collected in pre-washed plastic bottles. The un-acidified sampling bottles were carefully filled just to overflowing to ensure no air bubble was trapped inside the sample container. The samples were labelled, brought to the laboratory and stored at 4 °C to avoid any major chemical alteration prior to analysis. Samples for cation analysis were acidified (1% v/v Aristar nitric acid) on return to the UK prior to analysis. Dissolved organic carbon (DOC) samples were filtered (0.45µm) in the field using silver filters and were stored refrigerated in glass bottles prior to analysis. At each site samples were also collected for CFC-11 and CFC-12 analysis. CFC and SF_6 samples were collected unfiltered and without atmospheric contact in sealed containers by the displacement method of Oster (1994). This method ensures that the sample is protected from possible atmospheric contamination by a protective jacket of the same water. Stable isotope samples were collected in Nalgene bottles.

3.4 SAMPLE ANALYSIS

Un-acidified sub-samples were analysed for major anions using ion chromatography. Major and trace cations were analysed by ICP-MS. Stable isotope analysis ($\delta^{18}O$, $\delta^{2}H$) 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 (VSMOW). CFCs and SF_6 were measured by gas chromatography with an electron capture detector after pre-concentration by cryogenic methods, based on the methods of Busenberg and Plummer (1999). Measurement precision was within ±0.1‰ for $\delta^{18}O$ and ±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 (SF6) . Measurement of inorganic chemistry, DOC, stable isotopes values, CFCs took place at BGS laboratories in the UK.

3.5 INSTALLATION OF WATER LEVEL AND SEC LOGGERS

To record daily and seasonal fluctuations and abstraction effects on groundwater 6 piezometers (at depth of 150 mbgl) at Bhogpur, Kapurthala, Nakodar, Saroya, Sultanpur Lodhi and Tanda were drilled and instrumented with automatic water level recorders (Figure 6). Water levels in paired shallow piezometers are also monitoring to investigate interactions between shallow and deep aquifers. Four conductivity loggers are installed in shallow monitoring piezometers (60 mbgl) developed by Punjab Water Resources and Environment Directorate, Chandigarh, at sites Saroya, Bhogpur, Kapurthala and Sultanpur Lodhi (Figure 4). Preliminary results from the data loggers are shown in Appendix 2 (Figure 2) as holding data, a full download will be carried out in September after a full hydrological year.

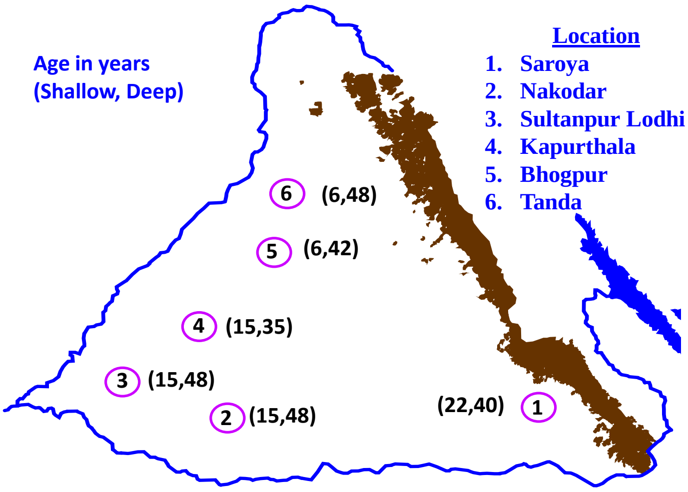


Figure 6. Locations of paired shallow and deep piezometers where continuous loggers are installed to monitor water levels and SEC (shallow sites)

4 Results

4.1 LONG-TERM CHANGES IN GROUNDWATER LEVEL

The long-term trends in groundwater levels for the 43 CGWB monitoring sites, with data covering 20 years or more, can be found in Appendix 1. Figure 7a shows a map of the trends in groundwater decline across the catchment, 8b the current pre monsoon groundwater level It can be seen that the sites with no long-term water level decline are found in the Kandi region or in close proximity to the R. Beas and Satluj, sites with moderate or high levels of groundwater decline are located away from the rivers or close to the foothills. There is an overall increase in the rate of groundwater level decline across plain towards the confluence (Figure 7a), which coincides with an absence of the canal distribution system. There is one noteworthy anomaly, Udhopur, to the south of Jalandhar 3, which has a shallow water table and which has no long-term decline in water level. This site is in close proximity to a large perennial tributary of the Satluj (See Figure 4) and the trends and groundwater levels at this site probably reflect hydraulic connectivity with this alluvial aquifer in close proximity to the river channel.

In the northern corner of the catchment groundwater levels are shallow and show no long-term trends (see Figure 7), this reflects the topography of the region and perhaps the sustained discharge from the Pong Dam (Himachal Pradesh) which maintains river/canal flow and groundwater levels in this region. Sites with the deepest groundwater levels (pre monsoon) are found in the Kandi region and in the central and SW region of the plains, this reflects the incised topography of the Kandi belt and the high level of abstraction within the shallow plains aquifer for irrigation. The region considered as the recharge zone for the plains aquifer, where there is a change in slope from the Kandi belt, generally have shallow groundwater levels and only moderate long-term declines in pre-monsoon groundwater levels.

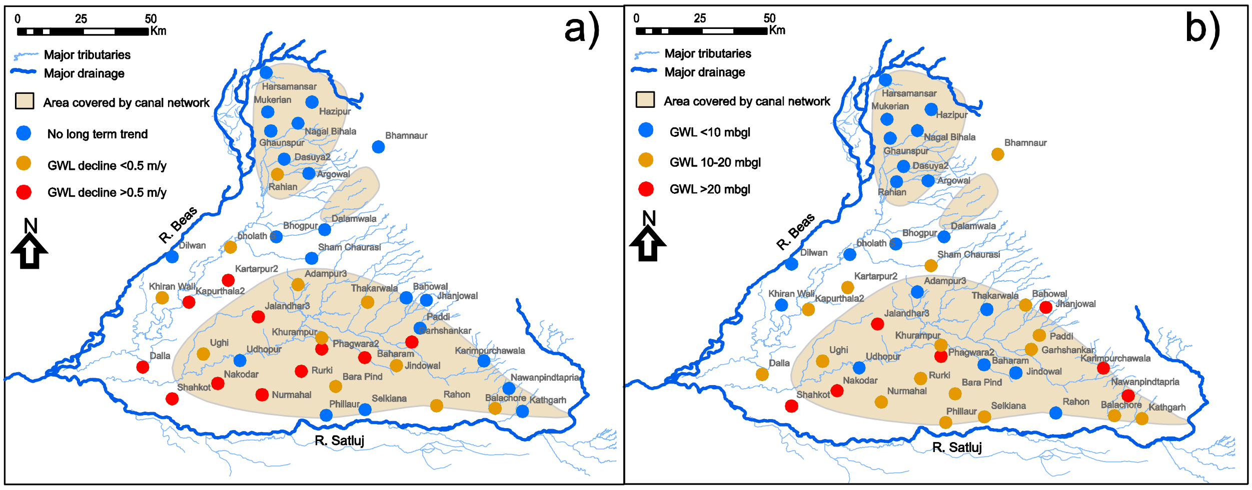


Figure 7. Spatial variation in (a) long-term (20 years) decline in pre monsoon groundwater level (b) pre monsoon groundwater level in 2010. source: CGWB.

4.2 STABLE ISOTOPES

Figure 8 (a-c) shows the stable isotope results in relation to the regional meteoric water line (RMWL) from Kumar et al. (2010), and calculated robust regression lines, from this study for shallow and deep sites under pre and post monsoon conditions. Figure 9 shows a plot of all the data in relation to previous studies of shallow and deep groundwater stable isotope results published by Rao et al (2014). Figure 10 shows a plot of spatial variation of stable isotope results across the Bist-Doab region.

Overall the shallow and deep values obtained in this study are consistent with those found by Rao et al (2014) in the same catchment (see Figure 8) with the exception of a few enriched outliers. There is a generally consistent result across the catchment which shows enriched samples in the shallow groundwaters compared to deep sites (see Figure 8 and 10) due to a greater component of relatively depleted recharge sources in deep sites from recharge zones up-gradient due to a the effects of the continental Raleigh distillation processes as the monsoon air masses track across India from the Bay of Bengal. The deep sites show no significant changes under pre and post monsoon conditions in all but one site (Hariana) which is found in the recharge zone.

The shallow boreholes at Amritpur (7.6 mbgl), in close proximity to the River Beas, show particularly depleted values for δ^{18}O and δ^{2}H, suggesting that there is significant surface water-groundwater connectivity in this location. At this site the shift in δ^{18}O from -9.5 to -8.9 between pre and post monsoon conditions suggests that this process is highly dynamic and operating within a sub 4 month time frame in response to post monsoon recharge from the Beas to the adjacent shallow alluvial aquifers. In contrast, the deep site at Amritpur (76 mbgl) showed no changes (-6.9) both pre and post monsoon. The highly enriched δ^{18}O values at Arjanwal in the shallow groundwaters (-2 and -4.8, See Figure 10) suggest that there are significant sources of shallow recharge water at this location exhibiting signs of evaporative fractionation prior to recharge.

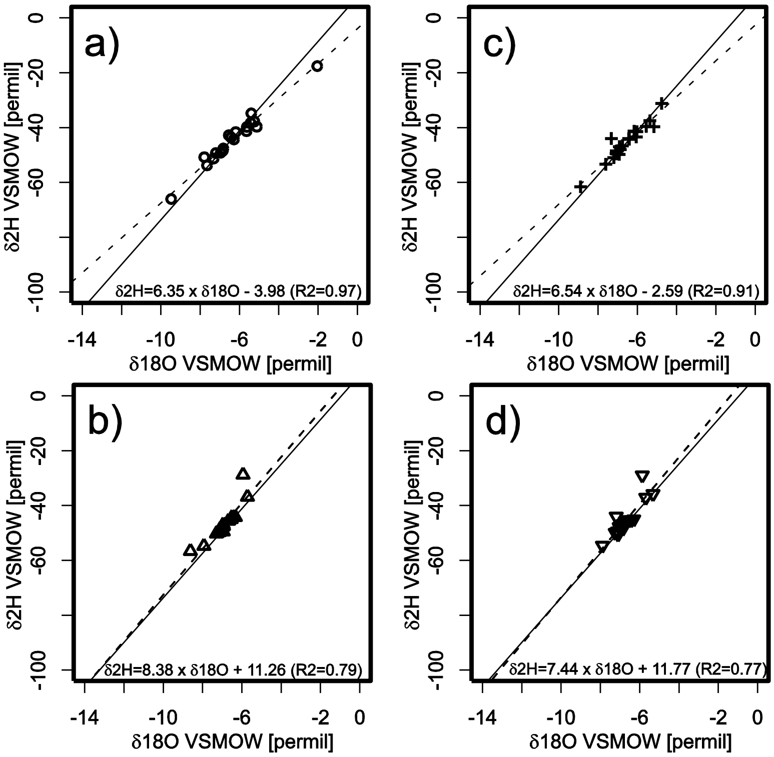


Figure 8. Stable isotope results (δ^{18}O vs δ^{2}H) for (a), shallow sites pre monsoon (b), deep sites pre monsoon (c) shallow sites post monsoon and (d). deep sites post monsoon. Solid line shows the RMWL and dashed line the robust regression line for the data.

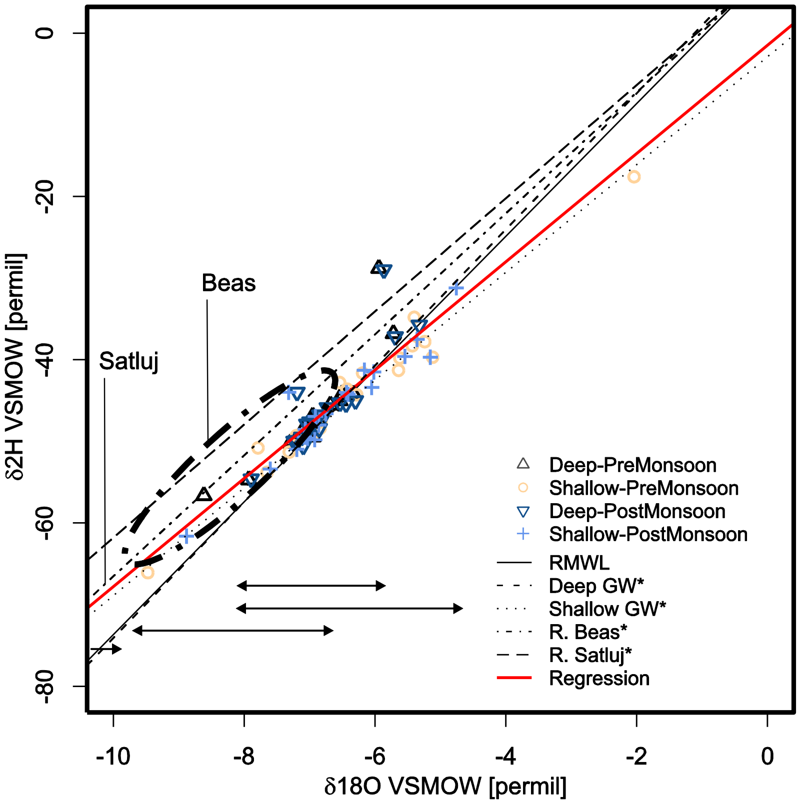


Figure 9. Stable isotope results (δ^{18}O vs δ^{2}H) for all data in comparison with published regression lines for shallow, deep groundwater across the catchment and surface waters. * Regression lines from Rao et al., (2014).

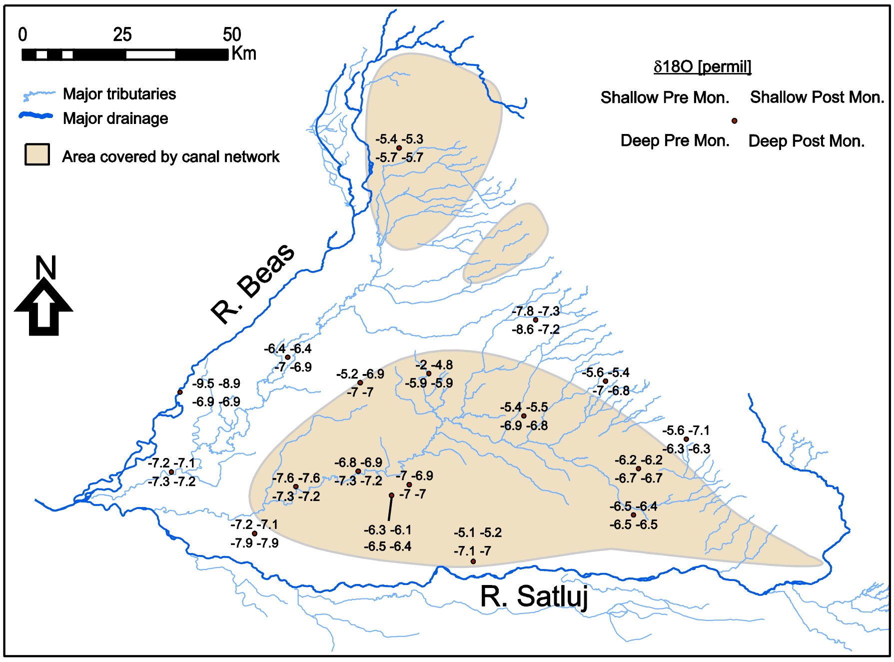


Figure 10. Spatial and temporal variation in stable isotope results ($\delta^{18}O$) across the Bist-Doab

4.3 DISSOLVED GASES (CFC-12 AND CFC-11)

Table 3 shows the results for CFC-11 and CFC-12 concentrations in groundwaters, modern fractions and estimated (PFM) MRTs for sites using CFC-12 data. A recharge temperature of 26 °C was used to calculate MRTs, the average value obtained from field observations. Figure 11 and 12 shows the CFC-12 and CFC-11 results, presented as the fraction of modern water, for all the sites in this study. It can be seen that only a handful of samples show signs of significant CFC-12 contamination compared to CFC-11. Figure 13 shows the model mean residence times (MRT) for groundwater estimated using CFC-12 data and a piston flow model, samples that had a modern fraction >1.1 were excluded from this analysis due to likely contamination.

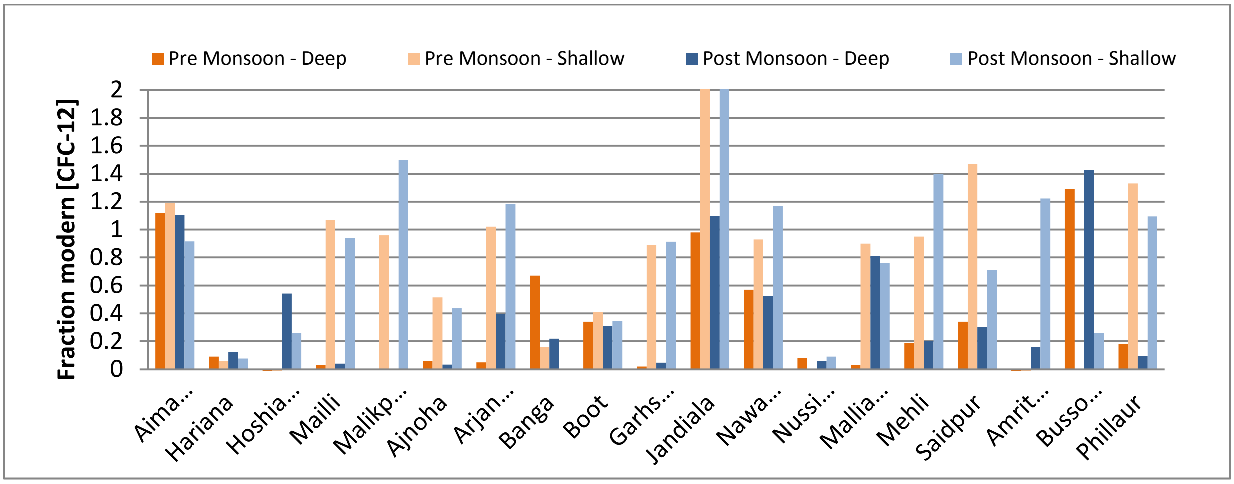


Figure 11. CFC-12 results presented as the fraction of modern water. Hydrogeological setting for sites; Amia M.-Malikpur (Zone 1, Kandi); Ajnoha-Mehli (Zone 2, Plains); Saidpur – Phillaur (Zone 3, floodplain/confluence). Data missing from Hoshiarpur and Amritpur.

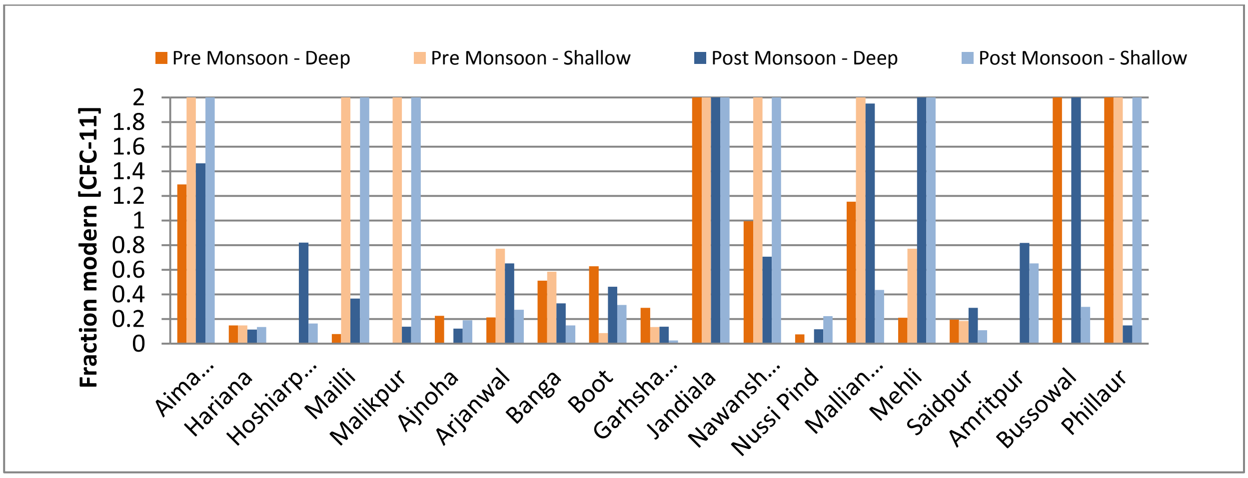


Figure 12. CFC-11 results presented as the fraction of modern water. Hydrogeological setting for sites; Amia M.-Malikpur (Zone 1, Kandi); Ajnoha-Mehli (Zone 2, Plains); Saidpur – Phillaur (Zone 3, floodplain/confluence). Data missing from Hoshiarpur and Amritpur.

Table 3. CFC-12 and CFC-11 concentrations, modern fractions and mean residence times

	Shallow					*Deep*				
	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12	CFC-12	CFC-11	CFC-12	CFC-11	CFC-12
	pmol/L	pmol/L	Mod. Fr.	Mod. Fr.	MRT* -Years	pmol/L	pmol/L	Mod. Fr.	Mod. Fr.	MRT –Years*
Pre-monsoon										
Aima Mangat	1.75	2.23	1.19	0.95	0	1.66	1.29	1.12	0.55	0
Hariana	0.09	0.15	0.06	0.07	54	0.13	0.15	0.09	0.07	51
Hoshiarpur	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Mailli	1.58	2.95	1.07	1.26	0	0.05	0.08	0.03	0.03	59
Malikpur	0.81	3.94	0.96	1.32	22	0.00	0.00	0	0	68
Ajnoha	N/A	N/A	0.51	N/A	18	0.09	0.23	0.06	0.1	54
Arjanwal	1.51	0.77	1.02	0.33	0	0.07	0.21	0.05	0.09	55
Banga	0.23	0.58	0.16	0.26	47	0.96	0.51	0.67	0.22	32
Boot	0.60	0.09	0.41	0.04	39	0.50	0.63	0.34	0.27	41
Garhshankar	1.27	0.14	0.89	0.06	26	0.03	0.29	0.02	0.13	63
Jandiala	23.57	163.58	16.01	69.66	>Mod	1.44	9.63	0.98	4.1	22
Nawanshahr	1.37	2.73	0.93	1.16	24	0.84	1.00	0.57	0.42	34
Nussi Pind	0.00	0.00	0	0	68	0.12	0.08	0.08	0.03	52
Mallian Kalan	1.32	3.06	0.9	1.3	25	0.05	1.16	0.03	0.49	59
Mehli	1.41	0.77	0.95	0.33	23	0.28	0.21	0.19	0.09	46
Saidpur	2.16	0.18	1.47	0.08	>Mod	0.51	0.20	0.34	0.08	41
Amritpur	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bussowal	0.00	0.00	0	0	68	1.90	2.39	1.29	1.02	0
Phillaur	1.96	8.23	1.33	3.5	>Mod	0.26	3.18	0.18	1.35	46
Mean	2.5	11.8	1.6	5.0	29.6	0.5	1.2	0.4	0.5	42.5
Median	1.3	0.8	0.9	0.3	24.5	0.3	0.3	0.2	0.1	46.0
Post-monsoon										
Aima Mangat	1.35	4.18	0.92	1.78	24	1.62	1.47	1.10	0.62	0
Hariana	0.11	0.14	0.08	0.06	52	0.18	0.11	0.12	0.05	48.5
Hoshiarpur	0.38	0.17	0.26	0.07	43	0.80	0.82	0.54	0.35	35
Mailli	1.39	2.61	0.94	1.11	23.5	0.06	0.37	0.04	0.16	57
Malikpur	2.20	2.26	1.50	0.96	>Mod	0.00	0.14	0.00	0.06	68
Ajnoha	0.64	0.19	0.44	0.08	38	0.05	0.12	0.03	0.05	58
Arjanwal	1.74	0.28	1.18	0.12	0	0.58	0.65	0.39	0.28	39
Banga	0.00	0.15	0.00	0.06	68	0.32	0.33	0.22	0.14	44
Boot	0.51	0.32	0.35	0.13	40	0.45	0.46	0.31	0.20	41.5
Garhshankar	1.34	0.03	0.91	0.01	24	0.07	0.14	0.05	0.06	56
Jandiala	11.58	107.79	7.86	45.90	>Mod	1.62	3.46	1.10	1.47	0
Nawanshahr	1.72	3.37	1.17	1.44	>Mod	0.77	0.71	0.52	0.30	35.5
Nussi Pind	0.13	0.23	0.09	0.10	51	0.09	0.12	0.06	0.05	54
Mallian Kalan	1.12	0.44	0.76	0.19	28	1.19	1.95	0.81	0.83	26.5
Mehli	2.06	3.73	1.40	1.59	>Mod	0.29	2.63	0.20	1.12	45
Saidpur	1.05	0.11	0.71	0.05	29.5	0.44	0.29	0.30	0.12	41.5
Amritpur	1.80	0.65	1.22	0.28	0	0.23	0.82	0.16	0.35	46.5
Bussowal	0.38	0.30	0.26	0.13	43	2.10	2.65	1.43	1.13	>Mod
Phillaur	1.61	4.12	1.09	1.76	0	0.14	0.15	0.09	0.06	50.5
Mean	1.6	6.9	1.1	2.9	30.9	0.6	0.9	0.4	0.4	41.5
Median	1.3	0.3	0.9	0.1	29.5	0.3	0.5	0.2	0.2	44.5

*Piston flow model used to estimate MRT. Mod. Fr = modern fraction

Table 3 and Figures 11 and 12 show that for most locations the shallow boreholes had significantly higher CFC concentrations and corresponding modern fractions. Shallow groundwaters were shown to have significantly younger MRTs compared to deep groundwater samples (Figure 13). Median MRTs were comparable for deep sites pre and post monsoon, while for shallow groundwaters MRTs were shifted towards younger residence times during post monsoon sampling, although this is not statistically significant (p=0.05).

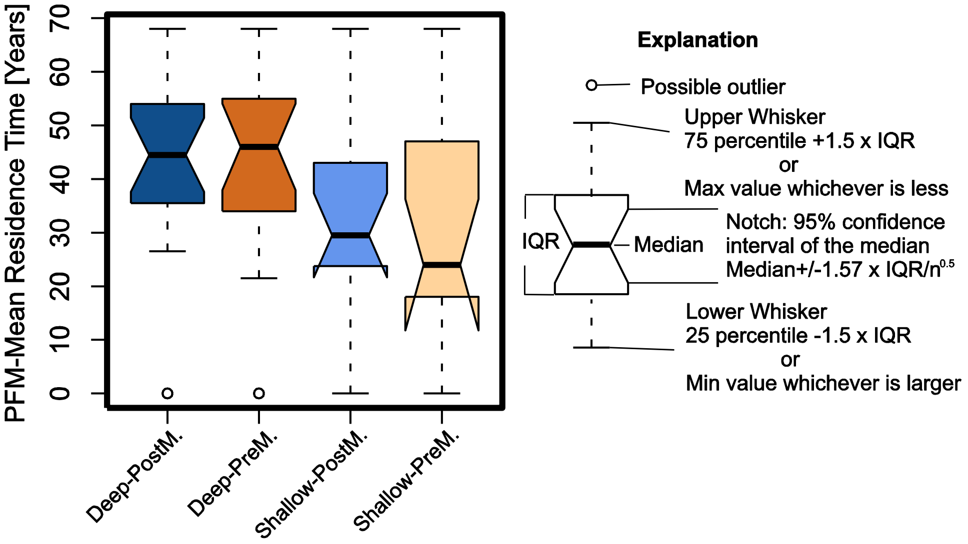


Figure 13. Notched box-plot of CFC-12 piston flow model Mean Residence Time (MRT) grouped by borehole depth and pre/post monsoon conditions

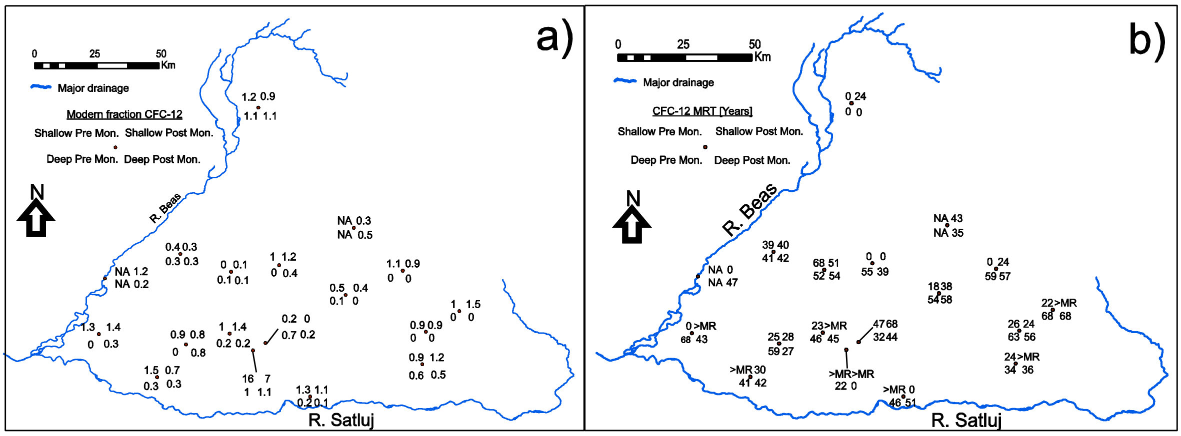


Figure 14. Spatial variation in CFC-12 modern fractions and MRTs

Figure 14 shows that there is no clear spatial relationship across the catchment for MRT in deep groundwaters, however it is noteworthy that the sites with the youngest deep groundwaters were found in the region of rapidly declining groundwater levels (e.g. Jandiala with MRTs between 0-22 years) and in the recharge area (Amia Mangat) which gave modern recharge values. Overall the deep groundwaters have median MRTs of 45 years, while the shallow groundwaters have median MRTs ca.30 years. Some locations in the region of rapidly declining groundwater levels (e.g. Bussowal, Mallian Kalan Jadiala and Arjanwal) had deep groundwaters that showed significantly younger MRTs post monsoon (43, 27, 0 and 39 years respectively) compared to pre monsoon (68, 59, 22 and 55 years) suggesting rapid pumping induced vertical leakage of modern water to depth during the monsoon.

4.4 NITRATE, CHLORIDE AND SEC

A complete table of summary statistics for major and trace elements is given in Appendix 1. Figure 15 shows box-plots for nitrate, chloride and SEC data grouped by borehole depth and pre/post monsoon conditions. Figure 16 shows cross-plots of total borehole depth vs NO_3, Cl, SEC and MRT. There is a consistent trend of significantly lower SEC and lower concentrations of Cl and NO_3 in the deep groundwater, this is strongly suggestive of anthropogenic sources of contamination within the shallow aquifers, and migration to depth at some locations. Overall, median concentrations are below 50 mg/L (WHO drinking water limit), however, there are a few sites where this is exceeded in both the shallow and deep sites. Median values for all three parameters in the shallow groundwater, were lower post-monsoon compared to pre-monsoon. This suggests a dilution effect in the shallow groundwater due to rapid meteoric monsoon recharge. While median concentration of nitrate in the deep groundwater are low, <5 mg/L, there are a significant number of sites which show concentrations >10 mg/L, which suggests that contamination from shallow sources may be mobilised and flushed to depth within the aquifer. A significant proportion of shallow sites have low nitrate concentrations and high SEC, this point to natural attenuation of nitrate in shallow aquifers in some situations, likely linked to redox controls and availability of DOC in the shallow aquifers. The low SEC in most of the deeper sites also indicates the lack of evidence for saline groundwater at depths of 150 m within this Doab.

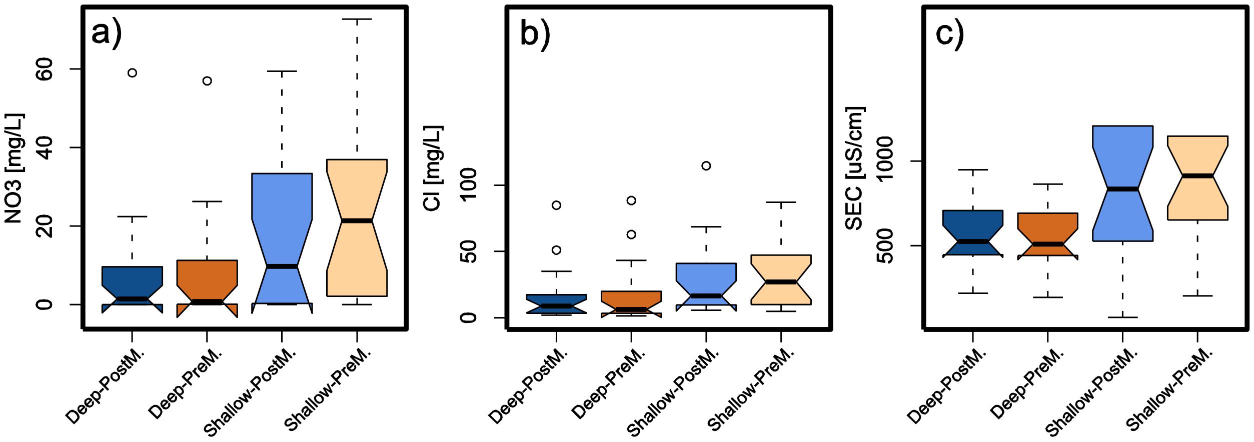


Figure 15. Notched box-plot of a) NO_3, b) Cl and c) SEC grouped by borehole depth and pre/post monsoon conditions.

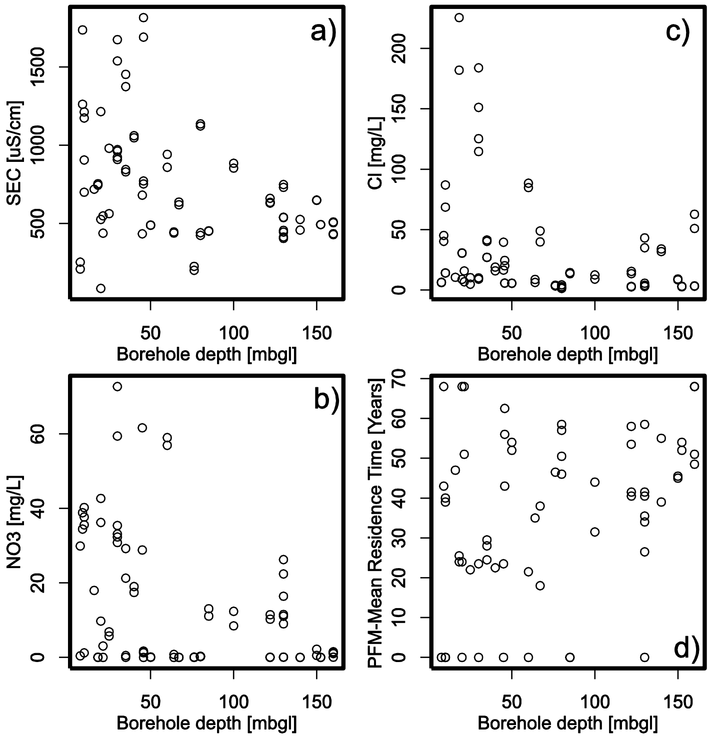


Figure 16. Cross-plot total borehole depth vs a) SEC, b) NO_3, c) Cl and d) MRT

4.5 TRACE ELEMENTS

Figure 17 shows box plots for selected trace elements of particular significance in terms of drinking water quality (e.g. As, F, Se, U, Fe and heavy metals) and groundwater residence times /geochemical evolution due to mineral dissolution processes (e.g. As, Mo, U). All groundwater samples in this study had dissolved As and F concentrations below 10 µg/L and 1.5 mg/L (WHO drinking water guideline values). Iron concentrations were generally below 500 µg/L except for some shallow sites, where overall Fe concentrations were significantly higher during post monsoon conditions and were >2000 µg/L in a few instances. Selenium concentrations were <10 µg/L in deep sites, however there were significantly higher concentrations in shallow groundwater, occasionally exceeding concentrations of 20 µg/L. Median concentrations of Cd, Pb, Cr, Cu, Ni and Zn were all significantly higher in shallow sites compared to deep sites, suggesting an anthropogenic source of contamination. Lead concentrations were generally below 10 µg/L, however there were 5 occasions where concentrations in shallow groundwater exceeded 20 µg/L. The heavy metals and Se appear to have a shallow source, anthropogenic contamination from waste water is a likely source for the former while perhaps enhanced Se concentrations in soils may be the source of enhanced Se in shallow groundwaters (Dhillon and Dhillon 2003).

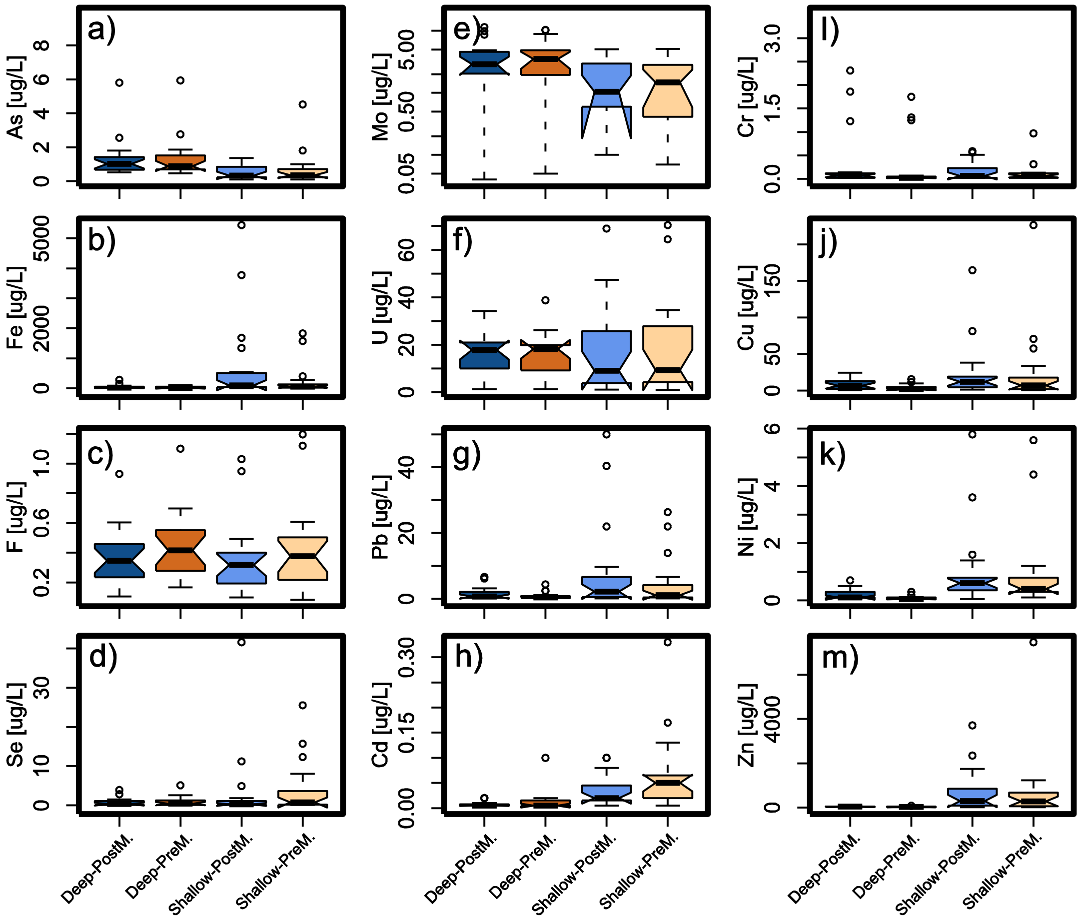


Figure 17. Notched box-plots of selected trace elements a) As, b) Fe, c) F, d) Se, e) Mo, f) U, g) Pb, h) Cd, i) Cr, j) Cu, k) Ni, m) Zn grouped by borehole depth and pre/post monsoon conditions.

Median concentrations of U, Mo and As were higher in the deeper sites compared to the shallow sites. Median concentrations for uranium in deep sites are >15 μg/L (WHO provisional guideline value is 30 μg/L). This guideline value for U is based on daily water consumption of 2 L/day which may not be realistic for NW Punjab, particularly during the hot season. These trace elements and others (e.g. Sr, Li, Rb) can be used as traces of groundwater evolution due to mineral dissolution processes and are therefore tracers of groundwater residence times (e.g. Edmunds et al., 2003). These results suggests that a major control on trace element concentrations, for elements which are not limited by mineral saturation, is groundwater residence time and water-rock interactions, however, anomalous high concentrations for U, Se and Mo in some shallow groundwaters also suggests a redox controls on element concentrations may also be important in some instances.

Figure 18 shows a cross plot of MRT vs four common chemical indicators of groundwater residence time (Mo, NO_3, Mg/Ca and Sr). There is a general trend of increasing Mo, Sr and Mg/Ca with increasing MRT and a decreasing trend in NO_3 with increasing MRT, together these highlight residence time controls on natural trace element compositions and anthropogenic contamination in groundwater. The variation in trace element composition (i.e. the noise in the trend) for samples with a given MRTs also suggests that mixing processes occurring at sites are important in controlling chemical compositions of groundwater and may reflect anthropogenic induced mixing due to intense pumping.

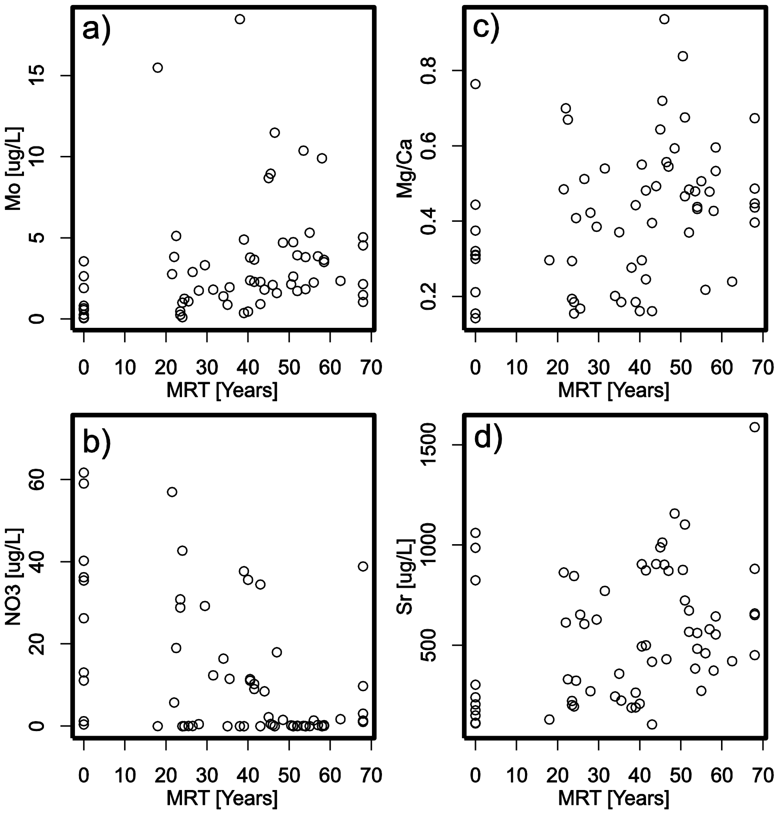


Figure 18. Cross-plot of MRT vs a) Mo, b) $\mathbf{NO_3}$, c) Mg/Ca and d) Sr

5 Discussion

5.1 GROUNDWATER FLOW AND RECHARGE PROCESSES: EVIDENCE FROM NATRUAL AND ANTHROPOGENIC TRACERS

A range of natural and anthropogenic tracers have been used in this study to understand, groundwater flow processes, anthropogenic contamination, and the natural geochemical evolution of groundwater in the Bist-Doab. Stable isotope results confirm the largely diffuse meteoric sources of recharge across the catchment in both the shallow and deep groundwater, which have significant overlap in terms of $\delta^{18}O$ vs $\delta^{2}H$ values. However, for most sites there is a significant difference between sable isotope values for the paired deep and the shallow groundwater, with deeper sites showing isotopically depleted signatures relative to the shallow samples. This is consistent with different recharge zones and processes for the paired sites at any given location, with the deeper sites have a greater component of water that was recharged some distance up-gradient (i.e. towards the recharge zone at the foot of the Shiwalik range). This source has a relatively depleted isotope signature due to Raleigh distillation processes (Figure 10). The values for the deeper sites ($\delta^{18}O$ values of ca. -7± 0.5) are consistent with continental scale depletion in meteoric recharge as monsoon air masses track from the Bay of Bengal ($\delta^{18}O$ values of ca. -4) in a NW direction, and the inland gradient of -2 per mil per 1000 km (Krishnamurthy and Bhattacharya 1991). There are also a small number of sites where the isotopic signatures for the shallow and deep sites are not significantly different, this suggests that there is a common local source or (mixtures of sources) for both depths and implies significant vertical leakage and mixing which may be enhanced due to pumping. This marks an important new finding and highlights the use of stable isotopes to delineate regional and local flow processes.

There are some shallow sites where there is evidence of recharge from fractionated sources of recharge, perhaps as a result of ponding, as well as surface water replenishment of aquifers adjacent to rivers (e.g. Amritpur, R. Beas) as a result of rising river stage in the post monsoon period. This is consistent with recent results presented by Sharma et al. (2014) which showed between 40-70% surface water recharge in shallow aquifers adjacent to the R. Beas at Naushera Pattan and Amritpur based on $\delta^{2}H$ values. Based on the results for shallow and deep sites, and comparing them to the published values for the Sutlej Canal (with a significantly depleted signature), there is no evidence of the Sutlej canal water being a significant component of recharge regionally – in fact the deep sites are more depleted than the shallow sites. However, this does not rule out significant recharge to shallow groundwater at locations close to canals or where canal leakage water is likely and canal water may be a significant component of irrigation water. The isotope values from the Beas River and the Kandi canal system, in the north of the Bist-Doab, overlap significantly with the groundwater isotope values, this means that delineating the influence of canal water in this region is not straightforward.

Trace elements were shown to be effective natural tracers of groundwater evolution as a result of mineral dissolution processes. For example, Sr, Mo, As, U, Mg/Ca all showed overall trends of increasing concentrations with increasing MRT. However, the trends showed a lot of scatter, suggesting perhaps that mixing processes, i.e. the convergence of groundwater with multiple residence times, is important in controlling trace element concentrations. Shallow sources of Se from soils rich in Se, observed across some in parts of the catchment (e.g. Dhillon and Dhillon 2003 and references therein), have been suggested as possible sources of high Se in shallow groundwater in these previous studies, it is also possible that high Se could also be associated with fertiliser use. This hypothesis was corroborated by evidence from this study which show enhanced Se concentrations in shallow groundwaters, although redox and pH controls are also likely to be locally important in mobilising trace elements and enhancing concentrations in shallow groundwater. Enhanced heavy metal (e.g. Pb, Cd, Cr) Cu, Ni and Zn in shallow groundwater compared to deeper aquifers, also suggests migration of anthropogenic sources of contamination in to the shallow aquifer system, most likely from waste water sources (Gopal et al., 2014).

Nitrate, Cl and SEC values are significantly higher in shallow groundwater due surface anthropogenic contamination from agriculture (e.g. fertiliser) and waste water sources. While there is evidence for denitrification in some sites (NO_3<0.03 mg/L) low concentrations were only detected in 18 % of samples. Groundwater in this region is moderately oxygenated (mean DO of 1.2 mg/L) and are oxidising (mean Eh of +256 mV), suggesting that NO_3 is a useful tracer of modern recharge and contamination in this setting. Shallow groundwater NO_3, Cl and SEC values show an overall downward shift in post monsoon conditions suggesting that there is a rapid dilution due to meteoric monsoon recharge. Overall the deep sites show consistent median values pre and post monsoon.

CFCs have been employed to trace recent recharge and estimate groundwater MRTs across the Bist-Doab. While there was evidence of contamination/degradation by CFCs at some sites, CFC-11 was much more affected by this than CFC-12. Where degradation or contamination were not occurring, there was generally good agreement between CFC-11 and CFC-12 MRTs and calculated modern fractions, providing important support for the interpretation of the CFC-12 data. The generally oxidising nature of the groundwater in this catchment also means that the use of CFC-12 as a conservative tracer is more reliable as CFC degradation can occur in sub-anoxic environments. Overall, shallow groundwater showed significantly younger MRTs compared to deep sites, as might be expected, although it is noteworthy that CFC-12 was detected in the majority of deep sites suggesting at least a component of modern recharge at depth. Even where concentrations were found to be greater than estimated modern recharge, indicating a potential source of local contamination, this data can still be used as a sensitive diagnostic tracer of connectivity between the shallow and deep aquifers and pathways for modern recharge.

Mean groundwater residence times in the shallow aquifers show a large range (0->50 years) with average values of 29 years and 30 years under post-monsoon and pre-monsoon conditions respectively. Using Darcy's law to calculate groundwater flow (Q) and literature values representative of alluvial sediments for hydraulic conductivity of 10-30 m/d (Rushton 1986); porosity of 0.2-0.3 (Todd 1959) and a regional gradient of 0.0004 (Bowden 1985) residence times of the order of ca.10^3-10^4 y in the deep aquifers (100-150 mbgl) 50 km from the recharge zone under natural flow regimes are estimated. Deep groundwater (>100 mbgl) have mean MRTs of 42 years, suggesting that the natural flow regimes for this aquifer system are highly perturbed by pumping, the young MRTs imply a significant component of recharge from vertical leakage induced by pumping from depth.

5.2 IMPLICATIONS FOR LONG-TERM GROUNDWATER SECURITY

There is clear evidence from historical groundwater level records that there has been a large decline in groundwater levels in shallow aquifers used for irrigation at a regional scale (ca. 20-25% of the Bist-Doab) over the last 20 years. Natural flow regimes and recharge in the shallow groundwater system are highly perturbed by the sustained pumping for irrigation, as shown by the MRT and stable isotope results. Work by Datta and Goel (1977), using tritium techniques, also showed that areas with irrigation had significantly enhanced recharge compared to non-irrigated locations. In many cases pre-monsoon groundwater levels are now >20 mbgl and in some areas falling at ca. 0.5 m per year, which has potential cost implications for long-term use of these shallow aquifers for irrigation. The area most affected by over-pumping for irrigation is the region SW of Adampur (i.e. zone 2 in Figure 3), the worst affected sites include Jalandhar, Phagwara, Nakodar and Shahkot, in the middle Doab and confluence, where pre-monsoon groundwater levels have declined by >20 m in the last 20 years.

There is evidence from the hydrographs that pumping and the declining pre-monsoon water levels are actually enhancing net recharge in the middle Doab and confluence region. However, in many of the sites in this region the post monsoon maximum are on a downward trajectory suggesting that net abstraction is outstripping the actual recharge.

A significant number of sites in the region of greatest groundwater decline (see Figure 7) show modern or over-modern CFC-12 recharge concentration suggests that the response in the shallow aquifers post-monsoon is due to rapid modern recharge. This has implications for the security of these shallow aquifers for i) sustained pumping towards the end of the pre-monsoon period, ii) the rapid migration of contaminants to depth within the aquifer, by-passing natural attenuation processes, and iii) inter-annual variability in rainfall and recharge during the monsoon. The higher groundwater levels (Figure 7) and modern CFC values obtained from shallow and deep sites at Aima Mangat (most northern site) suggest that recharge in this region may be from shallow modern sources, perhaps due to the larger density of canals used for surface water irrigation in this part of the catchment or due to leakage from the Pong Dam. The similar enriched isotope values ($\delta^{18}O$ values of ca. -5.4 to -5.7) for shallow and deep groundwater at this site suggests a common source of recharge at both depths and significant connectivity between the shallow and deep aquifers. The southern part of the Bist-doab also has a relatively high density of canals originating from the R. Satluj, which could be enhancing overall recharge in this region. However, the stable isotope data suggests that this is probably insignificant compared to shallow groundwater irrigation and enhanced monsoon recharge from meteoric sources as the distinct depleted $\delta^{18}O$ and $\delta^{2}H$ signature (<-10 and <-70 respectively) of R. Satluj (see Figure 9 and Rao et al., 2014) is not evident in any of the shallow groundwater in this region.

There is new evidence from groundwater dating using CFCs that some of the deep aquifers are also being replenished by a significant component of more recent recharge. This is most pronounced in the region of groundwater decline in the SW of the catchment where MRTs shift by up to 20 years to younger values in the deep sites post-monsoon, at two sites in the catchment post monsoon recharge is effectively modern recharge. There are two obvious explanations for this, either the deep abstraction sites at these locations are poorly constructed and what we are seeing is by-pass flow along the casing and the MRTs are an artefact of the borehole completion. The detailed logs and construction details available at some municipal sites suggest that these are well constructed sites which case out all but the lower portion of the borehole. Alternatively, the thick horizons of lower permeability material are leaky and allow significant vertical movement of groundwater from shallow aquifers to depth due to pumping. The fact that there is significant overlap between the region of long-term significant groundwater decline and the observed shifts in MRT post-monsoon at shallow and deeper sites suggest that it is unlikely to be just a case of poor borehole construction and is in fact an anthropogenic signal of pumping induced recharge and vertical leakage. One explanation for this is that there is a high degree of lateral variation in vertical permeability in the confining layers between the shallower and deeper aquifers, or indeed they may be discontinuous over relatively short distances. This results in zones or windows of high permeability within the confining horizons allowing rapid vertical migration of younger recharge to depth (e.g. Rushton, 1986; Rushton and Tiwari, 1989). These variations in vertical permeability are not likely to be a significant control on vertical groundwater flow under natural flow regimes in this mid-plains aquifer setting, due to the low relief and low hydraulic gradients, however they may become significant if an aquifer system is stressed by sustained pumping in both the shallow and deep aquifers.

5.3 NATURAL AND ANTHROPOGENIC IMPACT ON GROUNDWATER QUALITY

The shallow aquifers in this catchment are vulnerable to anthropogenic contamination from both agricultural (e.g. NO_3) urban sources (e.g. NO_3, heavy metals) and natural sources (e.g. Se in soils). In some shallow groundwater these contaminants are approaching or exceeding WHO guideline drinking water limits, e.g. for NO_3, Pb and Se. This shows the potential for contamination from surface sources are being flushed into the shallow aquifer, exceeding the capacity of the shallow aquifer to fully attenuate these contaminants through natural mechanisms such as sorption, dilution and denitrification. The enhanced pumping and resulting decline in water levels in some regions has meant that net recharge to the shallow aquifer has been enhanced, facilitating the rapid migration of recharge to depth within the shallow aquifer.

The leaky nature of the lower permeability horizons which separate the aquifer systems, demonstrated using a range of environmental tracers, means that the deeper groundwater is potentially vulnerable to vertical breakthrough of contaminants from shallow aquifers. There is evidence that this is already leading to nitrate contamination of some deep groundwater sources due to pumping enhanced vertical movement of groundwater. This has implications for the likely current levels and future trends for contaminants such as nitrate other anthropogenic contaminants such as pesticides. While these contaminants are not pressing concerns for groundwater security today they will need to be addressed in the long term.

In addition, some of the shallow groundwaters have SEC >1500 µS/cm, and have significantly higher SEC ($p<0.05$) compared to deep sites (Figure 15), with potential implications for the use of this water for irrigation in the long-term due to the build-up of salts in the unsaturated zone. Elevated SEC in the shallow groundwater is likely due to the use of fertilisers and manure as well as evaporative effects due to irrigation in this semi-arid climate. The current levels of SEC are not prohibitive for irrigation, but trends in salinity build up in the shallow groundwater system need to be monitored. These results are comparable with trends in the deterioration of groundwater quality found in other parts of Indian Punjab, Pakistan Punjab and northern China due to irrigation in semi-arid environments (Kumar et al., 2007; Kijne 1995; Ò Dochartaigh et al., 2010).

Enhanced residence times and mineral dissolution within deep groundwater has resulted in more elevated trace element concentrations for elements such as As, Mo and U compared to shallow groundwaters. In Bist-Doab this results in median U concentrations >15 µg/L and as high as 70 µg/L in some instances (over twice the WHO provisional guideline value of 30 µg/L). There are potential implications for radon contamination, and radiological aspects of toxicity that warrant further investigation. Evidence from this study shows that As contamination is not a major groundwater quality issue within the Bist-Doab where all dissolved As concentrations were <10 µg/L, and median concentrations for both deep and shallow groundwater were <2 µg/L. Fluoride concentrations were below WHO drinking water limits of 1.5 µg/L in all samples.

6 Conclusions

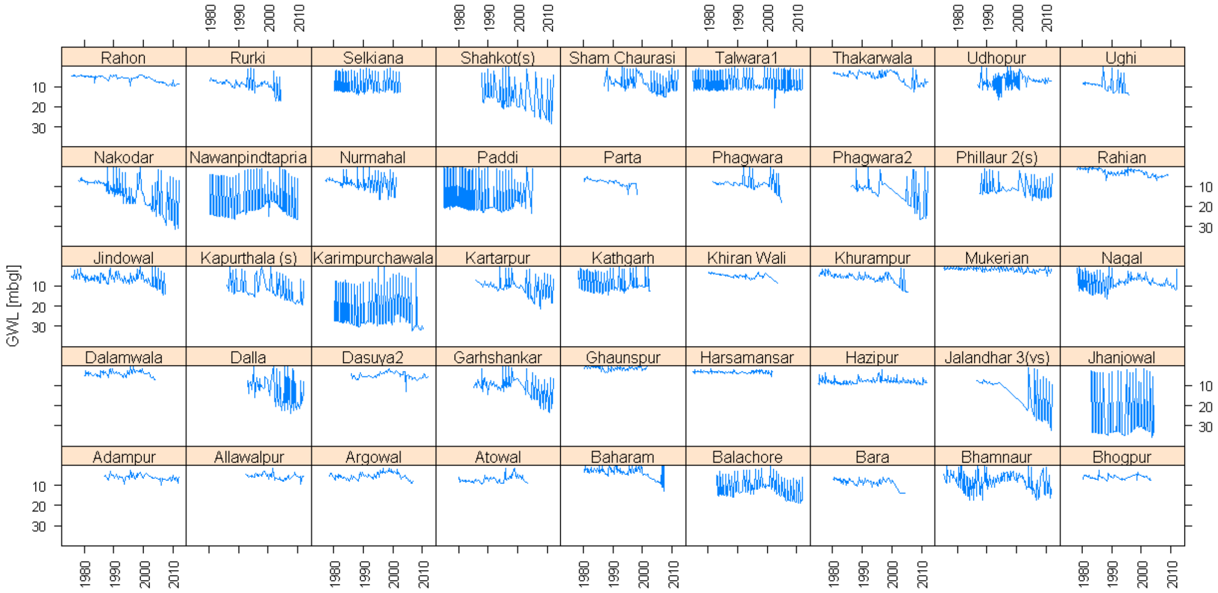
This report summarises initial findings from a hydrogeological case study focussed on investigating the response of groundwater resources in Punjab State, India to sustained long-term (>30 year) abstraction. The report covers a basic analysis of the long term groundwater level data (available from GWDB) in the region as well as the initial analysis and interpretation from a hydrochemical investigation carried out using a suite of environmental tracers (including dating tools and stable isotopes) to understand the sources of shallow and deep groundwaters in the Bist-Doab region of northern Punjab. Pre and post monsoon samples were collected across the Bist-Doab from paired shallow and deep sites and analysed by BGS. The findings from this case study have broad relevance across a large geographical area since broadly similar groundwater typologies extend across Indian Punjab, northern Rajasthan in the west, and upper Pakistan Punjab, as well as into neighbouring Indian states of the Ganges Basin in the east (e.g. Haryana).

Preliminary conclusions:

- Evidence from long-term groundwater monitoring shows declining trends in shallow pre-monsoon groundwater levels across a large part (20-25%) of the Bist-Doab.
- This is leading to enhanced recharge during the monsoon. For the most affected region of the Doab, declining post monsoon water levels suggest that abstraction for irrigation is outstripping the enhanced recharge potential.
- If the current situation is allowed to continue, in the long-term this will lead to a continued decline in shallow groundwater levels pre-monsoon, currently commonly found to be >20 mbgl, with future implications for irrigation.
- CFC groundwater age tracers show that median shallow groundwater MRTs of 25 years and 30 years under post-monsoon and pre-monsoon conditions. Deep groundwater (>100 mbgl) had median MRTs of 45 years irrespective of recharge conditions. Modern tracers were detected in all of the deep sites.
- Deep groundwater MRTs are much younger than would be expected under natural groundwater flow regimes. The region with long-term declining groundwater levels shows evidence of enhanced modern recharge in both shallow and deep groundwater, suggesting that there is a significant component of vertical leakage to deeper aquifers induced by long-term intensive pumping.
- Some of the shallow groundwaters have SEC >1500 μS/cm, with potential implications for the use of this water for irrigation in the long-term due to the build-up of salts in the unsaturated zone.
- There is evidence of nitrate breakthrough from the shallow groundwater to depth and this is likely to be enhanced in the future if the current increases in pumping from the shallow and deep aquifers continue. This has implications for future contamination of deep sources of drinking water from other anthropogenic contaminants such as pesticides.
- The naturally occurring contaminants arsenic and fluoride were present in concentrations below WHO guideline drinking water limits for all sites and median concentrations were below 2 μg/L and 0.4 mg/L respectively.
- Uranium concentrations in deep groundwater are significantly higher ($p<0.05$) compared to shallow groundwater, median values >15 μg/L, as a result of long residence times and mineral dissolution. There may be implications for elevated radon in deep groundwater, and this should be investigated.

Appendix 1

LONG-TERM TRENDS IN GROUNDWATER LEVEL IN THE BIST-DOAB



Appendix Figure 1. Long-term groundwater level trends for CGWB monitoring sites with records >20 years

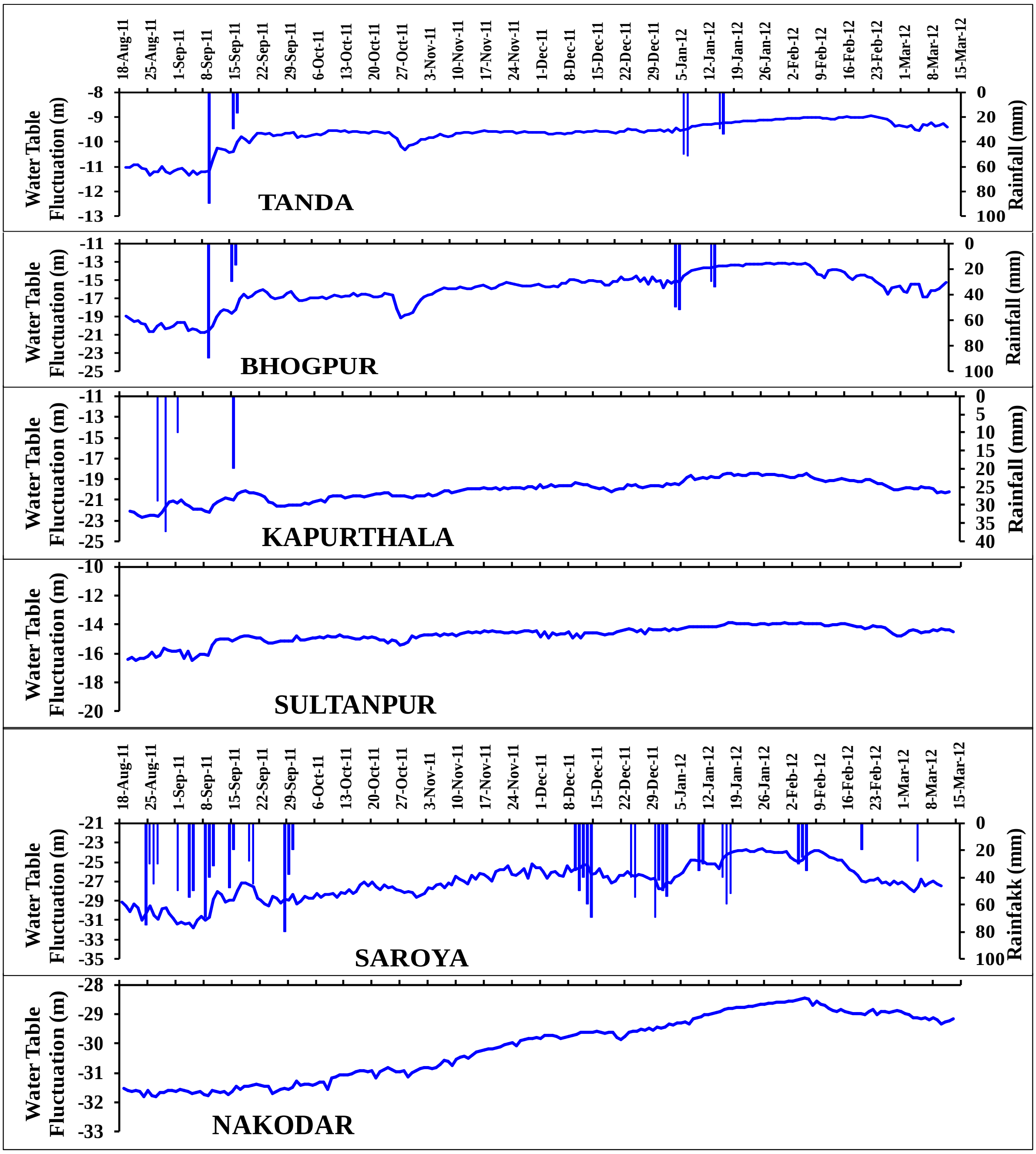
SUMMARY STATISTICS FOR GROUNDWATER CHEMISTRY

Appendix Table 1. Summary statistics for dissolved groundwater chemistry including field parameters. Mean values estimated using either the Kaplan-meier (KM) or maximum likelihood estimation (MLE) method.

Element	Unit	%cens	min	mean	max	sd	P5	P10	P25	P50	P70	P75	P80	P90	P95
Temp	°C	0	24	26.0	30.8	1.4	24	24	25	26	26.4	26.8	27	27.9	29
SEC	us/cm	0	85	748.3	1816	379.6	226	424	456	648	885	924	981	1262	1675
pH		0	6.31	7.2	8.22	0.4	6.61	6.78	6.95	7.2	7.34	7.4	7.43	7.61	8.04
Eh	mV	0	25	256.4	533	111.0	83.1	108	161	258.6	316	329	343	395	448
DO	mg/L	9	<0.01	1.2	7.8	1.8	NA	0.05	0.14	0.4	0.75	1.13	1.94	4.3	5.9
HCO_3	mg/L	0	87.8	393.1	859.4	158.5	152.4	212.1	263.3	395.0	459.6	474.2	490.0	616.8	653.4
Ca	mg/L	0	11.6	59.6	167.6	30.9	19.9	22.6	35.9	57	69.2	70.8	78.3	92.4	128.8
Mg	mg/L	0	5.13	22.9	46.48	11.9	5.87	8.88	12.15	21.22	31.88	32.72	34.69	38.85	43.48
Na	mg/L	0	5.8	66.9	262.3	56.1	7.5	15	29.7	46	76.5	85.8	96.8	158.2	179.4
K	mg/L	0	1.25	5.2	27.29	3.9	1.74	1.95	3.16	4.57	6.02	6.5	6.59	7.44	11.06
Cl	mg/L	0	1.3	31.4	225.5	45.4	2.7	3.1	5.6	13.5	31.8	39.6	41.4	87.0	151.2
SO_4	mg/L	3	<0.05	24.6	154.6	30.9	2.6	3.2	5.3	11.1	28.7	29.4	36.6	63.1	79.1
NO_3	mg/L	18	<0.03	14.1	72.7	18.4	NA	NA	0.0	3.0	19.0	26.2	30.8	38.8	59.0
Br	mg/L	11	<0.02	0.09	0.40	0.1	NA	0.01	0.03	0.06	0.12	0.14	0.15	0.23	0.29
NO_2	mg/L	41	<0.01	0.14	3.19	0.5	NA	NA	NA	0.01	0.03	0.03	0.06	0.28	1.15
F	mg/L	0	0.08	0.40	1.20	0.2	0.11	0.17	0.21	0.35	0.45	0.48	0.52	0.61	1.03
DOC	mg/L	6	<0.5	2.49	21.64	3.4	NA	0.59	0.81	1.26	2.26	2.64	2.82	5.12	9.08
Si	mg/L	0	3.58	12.1	17.55	2.9	5.54	8.38	10.74	12.2	13.81	14.16	14.45	15.3	16.28
Ba	µg/L	0	54.7	240.4	568.2	132.8	68.6	77.7	109.6	205.1	319.4	336.9	351.2	436.7	476.2
Sr	µg/L	0	95.6	542.7	1588.3	322.7	112.4	175	243.9	493.8	718.2	771	871	988.1	1060.5
Mn	µg/L	0	0.5	84.0	1050.3	175.8	1.7	3.1	8.9	21.1	57.9	71.9	93.6	227.5	410.9
Fe	µg/L	0	0.5	270.5	5441	815.5	2	5	12	44	78	101	128	477	1686
Li	µg/L	0	4	20.8	63	10.8	7	8	12	22	26	27	28	31	40
Be	µg/L	100	<0.01	0.0	<0.01	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
B	µg/L	0	15	121.7	380	85.5	18	25	47	112	164	174	194	248	265
Al	µg/L	14	<1	3.0	24	3.6	NA	NA	1	2	3	4	4	6	7
Ti	µg/L	42	<0.05	0.2	1.87	0.3	NA	NA	NA	0.07	0.1	0.11	0.14	0.21	0.6
V	µg/L	11	<0.2	1.8	12.1	2.0	NA	0.1	0.7	1.6	2.1	2.2	2.4	3.4	3.5
Cr	µg/L	0	0.02	0.3	3.51	0.7	0.02	0.02	0.02	0.02	0.11	0.13	0.23	1.23	1.86
Co	µg/L	14	<0.01	0.1	0.75	0.1	NA	NA	0.01	0.03	0.07	0.08	0.14	0.23	0.37
Ni	µg/L	0	0.05	0.6	5.8	1.1	0.05	0.05	0.1	0.2	0.5	0.6	0.8	0.9	3.6
Cu	µg/L	0	0.2	15.0	226.4	33.6	0.4	0.8	1.7	5.1	12	13.3	15.5	24.3	70.7
Zn	µg/L	0	2	380.1	7474.1	1013.9	3.8	6.5	17.4	41	154.9	276.5	455.8	864.7	1749.3
As	µg/L	0	0.1	1.2	9.83	1.8	0.15	0.19	0.34	0.69	1.03	1.11	1.37	1.87	5.8
Se	µg/L	0	0.05	2.3	41.6	6.0	0.05	0.05	0.05	0.4	1.2	1.2	1.7	4.9	12.3
Rb	µg/L	0	0.1	0.7	2.81	0.5	0.15	0.22	0.41	0.59	0.8	0.84	0.94	1.18	1.38
Y	µg/L	7	<0.005	0.0	0.172	0.0	NA	0.006	0.009	0.015	0.023	0.024	0.026	0.044	0.055
Zr	µg/L	100	<0.05	0.0	<0.05	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nb	µg/L	100	<0.02	0.0	<0.02	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mo	µg/L	0	0.04	3.2	18.48	3.4	0.1	0.31	0.91	2.14	3.65	3.82	4.53	8.68	10.37
Cd	µg/L	0	0.005	0.0	0.33	0.0	0.005	0.005	0.005	0.02	0.02	0.04	0.05	0.08	0.1

Pb	µg/L	0	0.06	3.8	49.95	8.5	0.1	0.14	0.23	0.72	2.44	3.19	3.46	6.81	21.97
Ag	µg/L	82	<0.05	0.04	0.56	0.09	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.08	0.13
Sn	µg/L	11	<0.02	0.2	1.88	0.3	NA	NA	0.05	0.07	0.16	0.19	0.25	0.43	0.52
Sb	µg/L	0	0.01	0.19	2.92	0.42	0.02	0.03	0.04	0.08	0.13	0.16	0.18	0.37	0.68
Cs	µg/L	57	<0.005	0.0	0.021	0.0	NA	NA	NA	NA	0.007	0.007	0.008	0.014	0.017
La	µg/L	7	<0.002	0.0	0.036	0.0	NA	0.003	0.004	0.006	0.008	0.009	0.01	0.014	0.018
Ce	µg/L	32	<0.002	0.0	0.042	0.0	NA	NA	NA	0.003	0.006	0.007	0.01	0.014	0.028
Sm	µg/L	36	<0.002	0.0	0.014	0.0	NA	NA	NA	0.003	0.004	0.004	0.004	0.005	0.006
Tb	µg/L	97	<0.002	0.0	0.002	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tm	µg/L	100	<0.002	0.0	<0.002	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Yb	µg/L	55	<0.002	0.0	0.008	0.0	NA	NA	NA	NA	0.002	0.002	0.002	0.004	0.004
Lu	µg/L	100	<0.002	0.0	<0.002	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tl	µg/L	99	<0.01	0.0	0.01	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ga	µg/L	86	<0.07	0.0205	0.0500	0.0311	0.0069	0.0084	0.0119	0.0175	0.0235	0.0256	0.0282	0.0362	0.0444
Pr	µg/L	89	<0.002	0.0009	0.0070	0.0018	0.0001	0.0001	0.0003	0.0005	0.0009	0.0011	0.0013	0.0021	0.0030
Nd	µg/L	95	<0.01	0.0030	0.0200	0.0063	0.0002	0.0004	0.0007	0.0016	0.0029	0.0034	0.0041	0.0068	0.0104
Sm	µg/L	36	<0.002	0.0030	0.0140	0.0033	0.0009	0.0012	0.0017	0.0025	0.0035	0.0038	0.0042	0.0055	0.0069
Eu	µg/L	86	<0.002	0.0012	0.0040	0.0018	0.0003	0.0004	0.0006	0.0010	0.0014	0.0016	0.0017	0.0023	0.0029
Gd	µg/L	70	<0.002	0.0019	0.0140	0.0035	0.0002	0.0003	0.0006	0.0012	0.0020	0.0023	0.0027	0.0043	0.0061
Dy	µg/L	71	<0.002	0.0018	0.0130	0.0032	0.0002	0.0003	0.0006	0.0012	0.0019	0.0022	0.0025	0.0038	0.0054
Ho	µg/L	96	<0.002	0.0008	0.0030	0.0009	0.0002	0.0003	0.0004	0.0006	0.0009	0.0010	0.0011	0.0015	0.0019
Er	µg/L	80	<0.002	0.0014	0.0110	0.0027	0.0002	0.0002	0.0004	0.0008	0.0014	0.0017	0.0019	0.0030	0.0043
Th	µg/L	92	<0.005	0.0025	0.0100	0.0033	0.0007	0.0009	0.0014	0.0021	0.0029	0.0031	0.0035	0.0046	0.0058
U	µg/L	0	0.93	16.9	70.389	14.8	1.193	1.981	5.43	15.124	21.37	23.1	25.441	31.48	47.38

INITIAL WATER LEVEL LOGGER DATA



Appendix Figure 2. Water level logger data from shallow sites in the Bist-Doab: Tanda, Bhogpur, Karpurthala, Sultanpur, Saroya and Nakodar

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