**Characterising groundwater-surface water connectivity in lower Gandak catchment, a barrage regulated biodiversity hotspot in the mid-Gangetic basin**

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**Highlights**

- Diffuse rainfall dominates groundwater recharge
- Groundwater baseflow is important for river ecology
- Evidence for localised groundwater recharge from canals and rivers
- Adequate flushing sustains low groundwater salinity
- Local redox conditions control groundwater As, Fe, Mn, $NO_3$ and U

**Abstract**

The alluvial aquifer system of the Indo-Gangetic Basin (IGB) is one of the world's most important freshwater resources, sustaining humans and river ecosystems. Understanding groundwater recharge processes and connections to meteoric and surface water is necessary for effective water resource management for human and wider ecological requirements. Parts of the mid-Gangetic Basin, across eastern Uttar Pradesh and Bihar, are characterised by stable long-term groundwater levels, high annual rainfall, and limited historical groundwater use compared to parts of Northwest India for example. In this paper we use a combination of environmental tracers and hydrograph observations to characterise sources of recharge and groundwater-surface water interaction using a transect approach across the catchment of the River Gandak, a major barrage-regulated tributary of the River Ganga. Stable isotope results show that the dominant source of groundwater recharge, in the shallow (0-40 m bgl) Holocene and underlying Pleistocene aquifer system (>40 m bgl), is local rainfall. The shallow Holocene aquifer is also supplemented by local recharge from river and canal seepage and irrigation return flow in the upper and mid parts of the catchment. These observations are corroborated by evidence from detailed groundwater hydrographs and salinity observations, indicating localised canal, river and lake connectivity to groundwater. In the middle and lower catchment, river discharge is dominated by groundwater baseflow during the peak dry season when barrage gates are closed, which contributes to ecological flows for endangered river dolphins and gharial crocodiles. Groundwater residence time tracers indicate active modern recharge in the shallow alluvial aquifer system across the catchment. In the shallow Holocene aquifer elevated arsenic (As), iron (Fe), and manganese (Mn) exceeded WHO drinking water guidelines in a minority of sites, and uranium (U) and fluoride (F) concentrations approach but do not exceed the WHO guideline values. These observations varied across the catchment with higher As, Fe and Mn in the upper and mid catchments and higher U in the lower catchment. Groundwater salinity was typically between 500 and 1000 μS/cm, and isolated higher salinity was due to recharge from flood-plain wetlands and lakes impacted by evaporation. At present, the Gandak catchment has relatively high

rainfall and low abstraction, which maintains stable groundwater levels and thus baseflow to the river in the dry season. Potential future threats to groundwater resources, and therefore river ecology due to the sensitivity to changes in baseflow in the catchment, would likely be driven by reductions in local monsoon rainfall, changes in water management practices and increased groundwater use.

**Keywords:** Groundwater, Indo-Gangetic Basin, recharge, surface-groundwater interactions, canal, River Gandak

## 1. Introduction

Groundwater is a critical resource for hundreds of millions of people in the Indo-Gangetic Basin (IGB) who rely on it for drinking water, agriculture and industry (MacDonald et al., 2016). Groundwater also sustains river flows and ecology through baseflow (Mukherjee et al. 2018). India’s annual rate of groundwater abstraction is the highest globally, now exceeding 200 $km^3\ yr^{-1}$, and continues to increase (Wada et al., 2010). Shallow groundwater has been used for centuries in the IGB, but over the last 40 to 50 years, and most markedly in the last 20 years, there has been a transition in food production from a reliance on surface water and rain-fed agriculture towards increased dependence on groundwater irrigation (Shah 2009). This has its roots in the agrarian economy of the region and the erratic rainfall patterns of the Indian monsoon (Gadgil et al., 1999, Sinha et al., 2007).

Groundwater recharge processes and connectivity with surface water varies across the IGB. Managing water resources effectively for human uses as well as river-floodplain ecosystems relies on a good spatiotemporal understanding of connectivity processes. Previous work in the IGB using environmental tracers and groundwater level time-series observations have illustrated the impact of excessive groundwater pumping for irrigation in depleting groundwater levels, and also the important role of surface irrigation in controlling groundwater recharge (Kumar et al., 2011, Sharma et al., 2014, Lapworth et al., 2015; 2018; MacDonald et al., 2016, Joshi et al., 2018, O’Keeffe et al., 2020). Several of these studies (e.g. Lapworth et al., 2015, Joshi et al., 2018) have explored the relative importance of current rainfall versus river and canal water for groundwater recharge using water stable isotopes supported by a range of residence time tracers. These studies have tended to focus on areas of the IGB that have experienced the largest depletion in groundwater levels (e.g. Lapworth et al., 2015; Joshi et al., 2018; van Dijk et al., 2019). However, there are many parts of the basin where long-term groundwater levels are shown to be stable over the last few decades (MacDonald et al., 2016), as a result of limited groundwater exploitation in relation to the role of surface water sources in maintaining groundwater levels.

The mid-Ganga region, specifically the lower portion of the Gandak catchment overlying the IGB aquifer in India, is one such area that has received less attention to date, and is the focus of this study (Figure 1). It was specifically chosen for its suitability for exploring groundwater interactions with river and canal water in an area of stable groundwater levels within the IGB.

The Gandak basin sustains thriving agriculture, capture fisheries, riverine forests and grasslands with large mega-herbivores and predators including the Tiger (*Panthera Tigris*). The river holds a globally significant breeding population of the critically endangered Gharial crocodile (*Gavialis gangeticus*), besides a population of the Ganges river dolphin *Platanista gangetica* (Choudhary et al. 2012). The Valmiki Tiger Reserve and a proposed Conservation Reserve on the downstream stretch of the river are part of the Gandak biodiversity conservation regimes. In 1960 a barrage was built across the river at the foot of the Shivalik-Himalayan hills on the India-Nepal border, which was followed by the expansion of a large canal network. This canal network supports agricultural production mostly in the dry-season, but suffers from major inefficiencies and has contributed to waterlogging in the command area (Chowdary et al., 2008, Khan et al., 2014). Compared to other regions within the IGB in Northwest India, groundwater pumping for irrigation and drinking water supply in the Gandak region is less intense and mainly restricted to the shallow part of the aquifer system (MacDonald et al., 2016, Bonsor et al., 2017).

In this paper, we examine evidence of whether local rainfall and surface water sources (*i.e.* leakage or seepage from canals, the River Gandak and other surface water sources) maintain groundwater recharge and groundwater discharge as baseflow to the river, in the Gandak catchment. We then extend this to discuss how anthropogenic hydrological interventions, especially flow regulation by a barrage and abstraction through canals, have altered groundwater recharge and flow processes within this sub-catchment of the IGB where rainfall is higher (> 1000 mm) and groundwater abstraction is not excessive. Our primary working hypothesis is that canal leakage/seepage and other surface water sources recharge the alluvial aquifer system, but this is largely restricted to the shallow upper part of the aquifer, and that the influence of canal leakage/seepage as a recharge source reduces as you move down catchment and away from the upper canal command area. We test the hypothesis using a suite of environmental tracers to characterise recharge sources and processes along a sampling transect from the upper to lower Gandak catchment (Figure 1) within the non-mountainous (plains) zone of the basin, and supplement this with new targeted high frequency groundwater level observations and spot river flow measurements.

## 2. Methods

### *2.1 Study area*

The River Gandak rises on the Tibetan plateau and flows through Nepal before entering India in north-west Bihar where the Shivalik mountains meet the alluvial plains. From there it flows southeast for 335 km before joining the River Ganga close to Patna (Figure 1a). The Gandak catchment area is 46,000 $km^2$, but this study is focussed on the downstream section of the Gandak catchment in India, which covers an area of 7600 $km^2$, and is henceforth referred to in this paper as the ‘catchment’. The River Gandak has the third highest contributing flow of any tributary to the Ganga (MacDonald et al., 2015), and is prone to periodic flooding (Chowdary et al., 2008). Long-term annual average rainfall in the catchment is c.1200 mm (Singh et al., 2008). The lower section of the catchment receives 800-1200 mm of rainfall annually and the upper section receives 1200-2000 mm annually (Sinha and Friend, 1994; Pai et al., 2014), with high inter-annual variability. Annual average discharge for the Gandak recorded at Dumariaghat is 1555 $m^3 s^{-1}$. The flow in the River Gandak has been shown to gain after the Barrage, reflecting in-catchment contributions to flow (Sinha and Friend, 1994).

The flow in the River Gandak is regulated by the Gandak barrage on the India-Nepal border, from where three main canal branches distribute water from the river: the Nepalese; western; and eastern canal command branches (Jha and Prasad, 2002). The eastern canal branch supplies Bihar and is within the current study area. Large scale irrigation using canal water began in the early 1970s (Jha and Prasad, 2002). The canal system is clay lined and leakage losses of up to 50% are reported increasing groundwater recharge, particularly in the uppermost section of the Eastern branch (Bonsor et al., 2017). There is intense use of canal water for irrigation in the northern section of the catchment and extensive use of shallow groundwater for irrigation across the whole catchment (Government of Bihar 2014; O'Keeffe et al., 2020). For much of the dry season, canal flows do not reach the southern section of the catchment and there was no change, between 2000-2012, in groundwater levels across the catchment in a recent study by MacDonald et al. (2016).

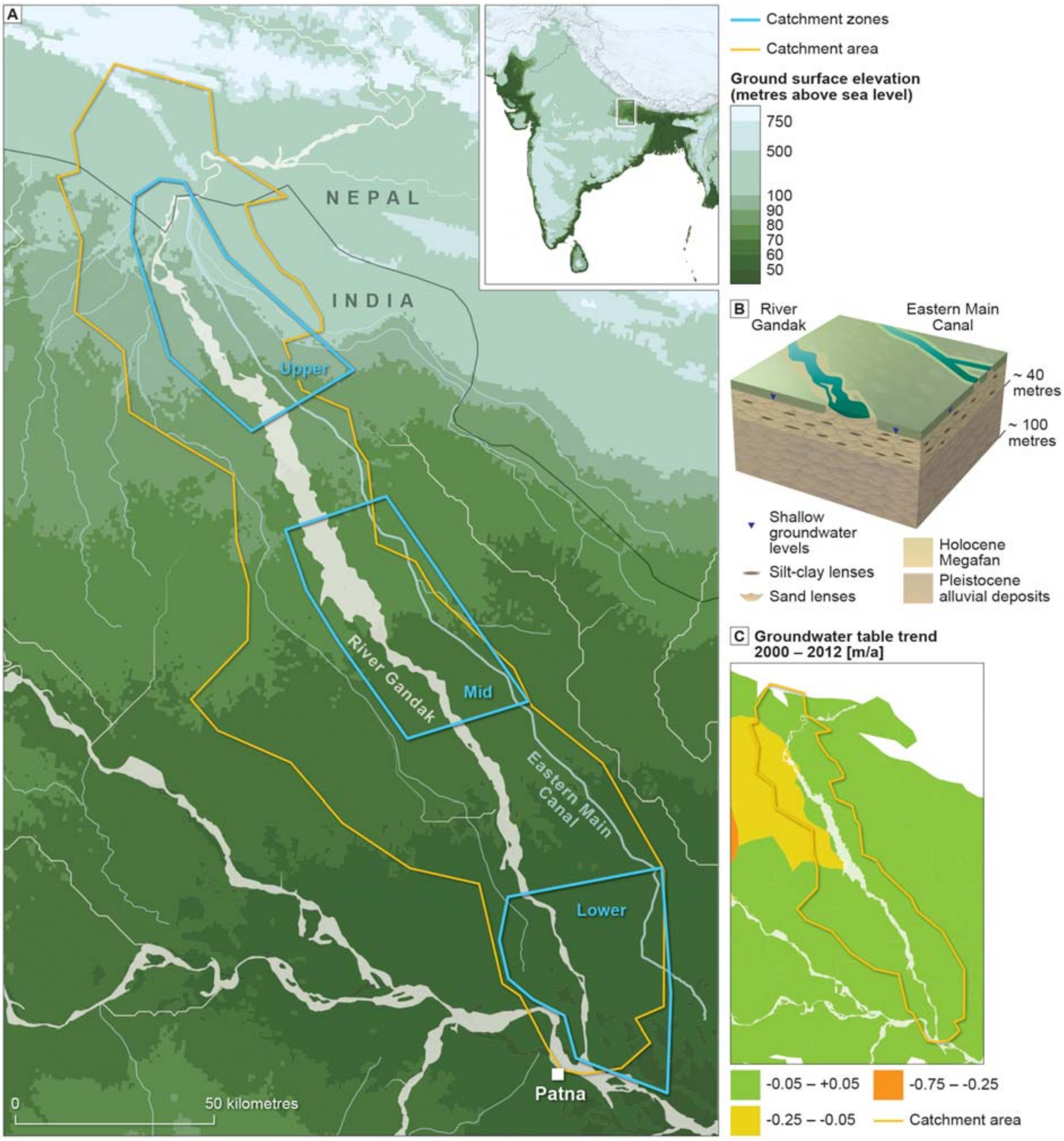


**Figure 1.** Study area location, sedimentology and long-term groundwater trends a) Gandak catchment and study zones in the upper, mid and lower Gandak, b) schematic sedimentary architecture of the Gandak megafan (adapted from Pati et al., 2019), c) long-term 2000-2012 groundwater trends for the Gandak and surrounding area (source MacDonald et al., 2016).

### *2.2 Hydrogeology and sedimentology of Gandak catchment*

The IGB is the largest area of modern alluvial sedimentation in the world, with sedimentary deposits up to several km deep in places, (Sinha and Sarkar, 2009; Densmore et al., 2016). Holocene and

Pleistocene alluvium form two distinct units within the overall IGB aquifer system, from which all groundwater in the basin is abstracted. At local scales, these sedimentary units are composed of alternating gravels, sands, silts and occasional clays, in sequences of channel and inter-channel deposits forming laterally discontinuous aquifer units, typically less than a few kilometres across (Samadder et al., 2011; Bonsor et al., 2017). At a basin scale, vertical connectivity reduces from proximal to distal regions as low permeability layers become more dominant (MacDonald et al., 2016, Bonsor et al., 2017).

The Gandak megafan directly underlies the study catchment, composed of Holocene alluvial sediments deposited by the River Gandak system to produce an alluvial plain with low relief (Sinha and Friend., 1994; Pati et al., 2019). The Holocene megafan sediments were deposited as the River Gandak migrated eastward, forming up to 40 m of mainly sand deposits with minor clay units, with the sands fining, and clay increasing, towards the distal parts of the megafan (Pati et al., 2019). There are very few gravel deposits in the megafan due to the trapping, abrasion and reworking of gravel within the streambed in Nepal (Sinha and Sarkar 2009; Dingle et al., 2017). The megafan deposits can form significant high permeability aquifers (Bonsor et al., 2017). Beneath the Holocene mega fan is a thick sequence of Pleistocene aged alluvium. There are very few boreholes that directly characterise these deposits in the Gandak, but the few that do indicate significant and extensive sand (Sinha et al., 2014). They are most likely similar to Pleistocene deposits elsewhere in the Ganga basin composed of alternating coarse and fine sands, silts and occasionally clays, deposited within sequences of channel and inter-channel deposits, with each package rarely more than a few kilometres across, and any one individual unit is generally less than 50 m thick (Bonsor et al,. 2017) (Figure 1b).

Mohindra et al (1992) provide a comprehensive assessment of the pedology of the Gandak megafan, and report a distinct increase in soil clay accumulation (illuviated clay) away from the Young Gandak Plain, close to the river, towards the Old Gandak Plain (see DEM on Figure 1a). This is accompanied by a significant increase in soil acidity moving from the Young Plain soils (pH 7.8-8.8) to the Old Plain soils (pH 5.8-6.2), related to the decalcification of parent material (Mohindra et al., 1992). Both the sedimentary architecture and these changes in soil characteristics within the catchment may influence localised recharge processes and shallow groundwater chemistry.

### *2.3 Water sampling and analysis*

A sampling transect down the catchment was established on the eastern side of the River Gandak, in the eastern canal command area. Samples were collected for different water sources (groundwater, surface water and rainfall) to characterise changes in groundwater and surface water down the transect. Sampling was focussed on three zones within the Gandak: the (i) upper (ii) mid and (iii) lower sections of the catchment (Figure 2). This enabled groundwater recharge processes to be evaluated in different parts of the catchment where the use of surface water for irrigation varies - from the intensive use of canal water in the upper and mid sections to lower use in the lower section. Boreholes were selected in consultation with local farmers to enable groundwater sampling.

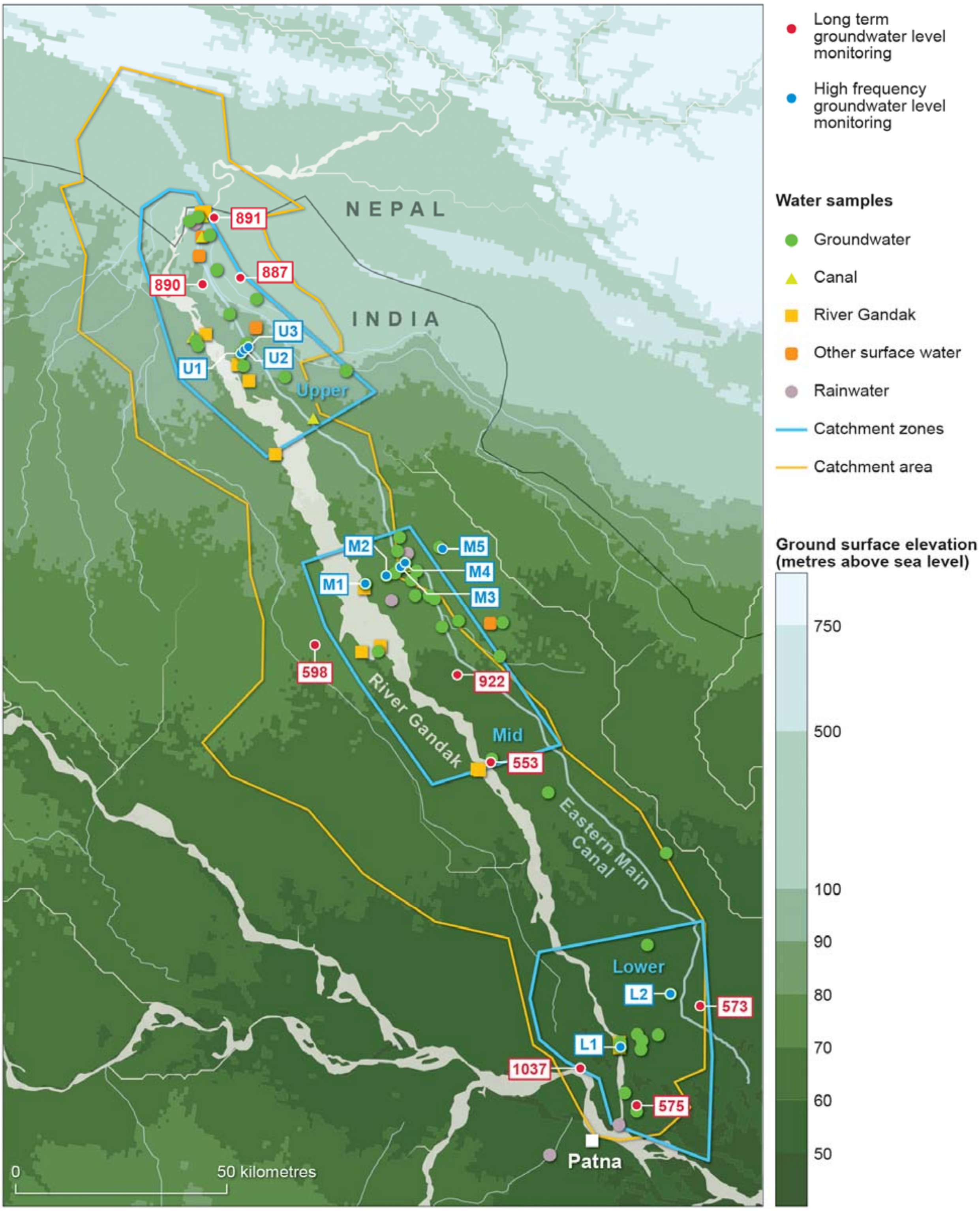


**Figure 2**. Sample sites and groundwater level monitoring points

Groundwater chemistry was sampled under pre-monsoon conditions following purging of boreholes and achieving stable readings for field parameters. A total of 61 groundwater samples was collected from existing boreholes from a depth range between <10-70 m below ground level (bgl), and a single sample from a deeper borehole at 150 m bgl. Eighteen River Gandak samples, 4 other surface water samples, 7 Gandak canal water samples and 18 rainfall samples were also collected. Some of the 61 groundwater samples, including handpumps, were taken from boreholes that were in regular use and therefore did not require extensive purging prior to sampling, other sites not in regular use were purged prior to sampling.

In total, 109 water samples were collected for stable isotope analysis; 13 samples for groundwater residence time analysis and 45 samples for inorganic chemistry analysis (O Dochartaigh et al., 2020b). A total of 55 of these surface and groundwater samples were measured for specific electrical conductivity (SEC) in the field, for the other grab samples where field measurements were not possible and laboratory SEC measurements were undertaken. Rainfall samples were collected using a totaliser with a tube and 'dip-in' design suitable for the climate of India, which minimises evaporative effects (IAEA/GNIP 2014). The presence of *kankar* carbonate deposits make the use of radio-carbon dating of groundwater problematic in this region, and elsewhere in NW India, and therefore other groundwater residence time tracers were used. Groundwater residence time tracers samples for chlorofluorocarbon (CFC)-11, 12 and sulphur hexafluoride ($SF_6$) were collected unfiltered, and without atmospheric contact, in sealed containers by the displacement method of Oster et al. (1996). A recharge temperature of 28 °C was assumed for calculating tracer concentrations. $SF_6$ data were corrected for excess air at 3 cc/L. All chemical analysis was undertaken at BGS geochemistry and groundwater tracer laboratories in the UK. Stable isotope results are reported as a deviation from Vienna Standard Mean Ocean Water (vs. VSMOW) in per mil (‰) difference using delta (δ) notation.

### ***2.4 Ground-water level monitoring***

Groundwater levels measured in the Gandak catchment over the period 1983 to 2013 were obtained from the Central Groundwater Board (CGWB) monitoring network (Macdonald et al., 2016). These time-series typically consist of 2-6 manual dips per year. Nine monitoring points were selected to assess long-term trends in groundwater levels across the three catchment zones (upper, mid and lower): seven to the east of the Gandak and two to the west.

Additionally, automatic groundwater level loggers, recording at 15-minute intervals, were installed in 10 boreholes in farmers' fields along three transects, one in each of the three zones (O Dochartaigh et al., 2020a). Six sites (U1-3 and M1-3) were newly constructed piezometers to a depth of 20 m. These were used to quantify detailed seasonal changes in groundwater levels and characterise responses along transects from the River Gandak to, and beyond, the Eastern Main Canal, as well as the possible effect of shallow groundwater pumping for irrigation. The observations span the period 1 April 2017 to 31 January 2019, but the exact period of monitoring was different between the boreholes, due to the different dates of their construction, or in one case (M5) the loss of the logger. The locations of the monitored boreholes in the three transects are shown in Figure 2.

### *2.5 Seasonal monitoring of river discharge and rainfall data*

River discharge was measured at reference sites in the three zones, at approximate distances of 0, 44, 88, 140, 190, and 295 km from the Gandak barrage in the: i) post-monsoon season (November 2017, when all barrage gates were open), and ii) summer (March 2018, when barrage gates were closed). River discharge measurements were undertaken using the velocity-area method and Manning's equation (from river energy slope and roughness coefficients). A decrease in discharge with increasing distance was regarded as contributions to recharge, and an increase was regarded as gains in discharge or base-flows contributed by the aquifer.

Estimates of daily rainfall for the three catchment zones were derived from the Indian Meteorological Department's 0.25° gridded dataset (Pai et al., 2014).

## 3. Results

### *3.1 Water stable isotopes*

Figure 3 shows a summary of the water stable isotope results as a cross-plot of $\delta^{18}O$ vs $\delta^{2}H$ for the full range of water types collected as part of this study. Groundwater and surface water results are differentiated by catchment zone (Figure 3b). An indicative binary mixing line between groundwater and surface water (Figure 3b) illustrates surface water-groundwater interactions and mixing between water from meteoric rainfall and surface water sources. The local meteoric water line and amount-weighted rainfall mean values are shown for comparison. A small sub-set of sites (n=3) showing significant enrichment (Figure 3a), from an oxbow lake sample and two shallow boreholes close to wetlands, are indicative of evapotranspiration processes prior to recharge.

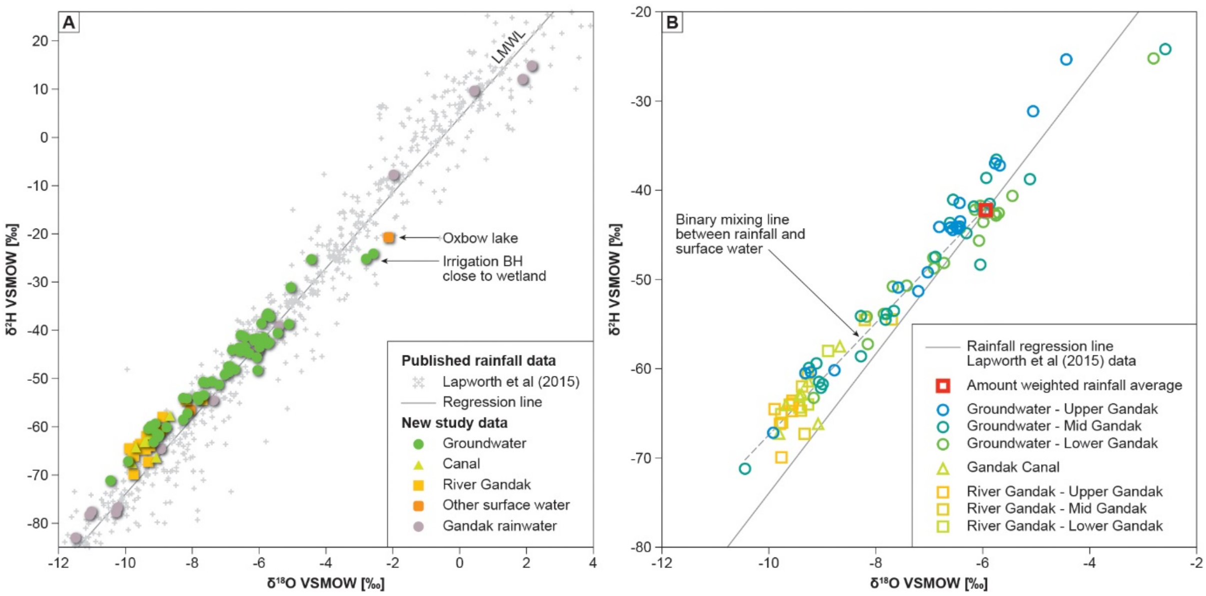


**Figure 3.** Water stable isotope results: a) all data by water type b) groundwater and surface water results by catchment zone (upper, mid and lower catchment). Local meteoric water line (LMWL) and amount-weighted rainfall mean from Lapworth et al. (2015) using data for NW India.

### *3.2 Groundwater residence time tracers*

The variations in groundwater residence time tracer concentration (CFC-12, CFC-11, $SF_6$) and salinity with total borehole depth are shown in Figure 4. There is an overall decrease in tracer concentrations in groundwater with depth (Figure 4a), but there is considerable variability within the shallow (<40 m bgl) groundwater system, within the Holocene aquifer, and there are few observations from the deeper (>40 m bgl) Pleistocene aquifer. Within the shallow aquifer, c. 30% of the observed tracer concentrations are indicative of dominantly recent recharge. The remaining 70% of samples from the shallow aquifer, and all from the deeper aquifer, all contain some modern tracers but are all are predominantly older water.  The upper catchment zone had the largest proportion of shallow (<40 m bgl) samples with high concentrations of modern tracers, for CFC tracers these were significantly higher than the other zones, however this was not found to be the case for $SF_6$ (Figure 4a). In the mid catchment, groundwater showed no evidence of changes in tracer concentration with depth, and shallow groundwaters had lower tracer concentrations compared to the other two zones (Figure 4a). There was also no marked change in salinity with depth (Figure 4b), but surface waters showed lower salinity and lower variability than groundwaters. The salinity of samples in the lower catchment zone are significantly higher for the Holocene aquifer (Figure 4b), compared to the upper and mid zones which have comparable SEC values (Figure 4b).

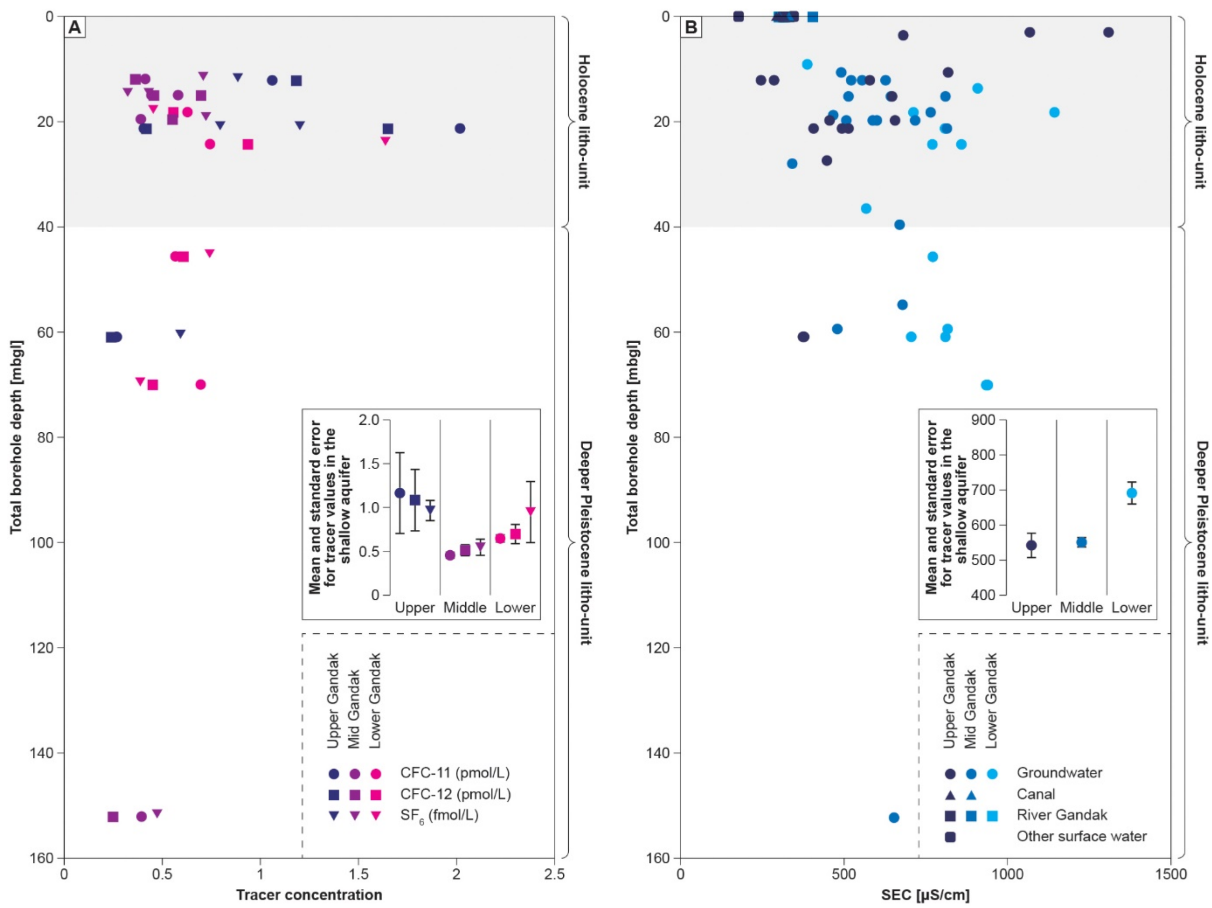

**Figure 4.** Groundwater residence time and surface and groundwater salinity results for upper, mid and lower catchment zones, as depth profiles. a) Tracer concentrations, b) Salinity plotted as SEC (μS/cm). Data is plotted using total borehole depth: casing depth information was not available.

### ***3.3 Inorganic hydrochemistry***

Depth variations for selected hydrochemical parameters in groundwater are shown with canal and river water data for comparison (Figure 5a-i). With the exception of dissolved organic carbon (DOC), surface waters have lower variability and lower concentrations for all parameters compared to groundwater, and $\delta^{18}O$ values are depleted and tightly clustered relative to groundwater. Several parameters for groundwater samples (e.g. stable isotopes, SEC, DOC, and some redox sensitive parameters, such as nitrate ($NO_3$), arsenic (As) and manganese (Mn), are characterised by higher variability in the shallow Holocene than in the deeper Pleistocene aquifer. Other parameters, including U, F and Fe, are variable in both shallow and deeper aquifers (Figure 5). The majority of groundwater samples have low nitrate (<5 mg/L $NO_3$) and As (<10 μg/L) concentrations. In a few groundwater samples (n=5) from the Holocene aquifer, As concentrations exceed the WHO drinking water guideline value of 10 μg/L (WHO 2017), but none exceed the Bureau of Indian Standards (BIS 2012) of 50 μg/L. Fluoride concentrations are all below 1.5 mg/L (BIS and WHO drinking water guideline value). For U no sites exceed Indian drinking water limit of 60 μg/L or WHO limit of 30 μg/L, but the highest U value (29.5 μg/L) approaches the WHO limit. Nine samples exceed the BIS limit of 0.3 mg/L for iron, and two samples exceed the BIS of 300 μg/L for manganese. DOC concentrations are all below 3 mg/L, but are higher in the shallow Holocene aquifer.

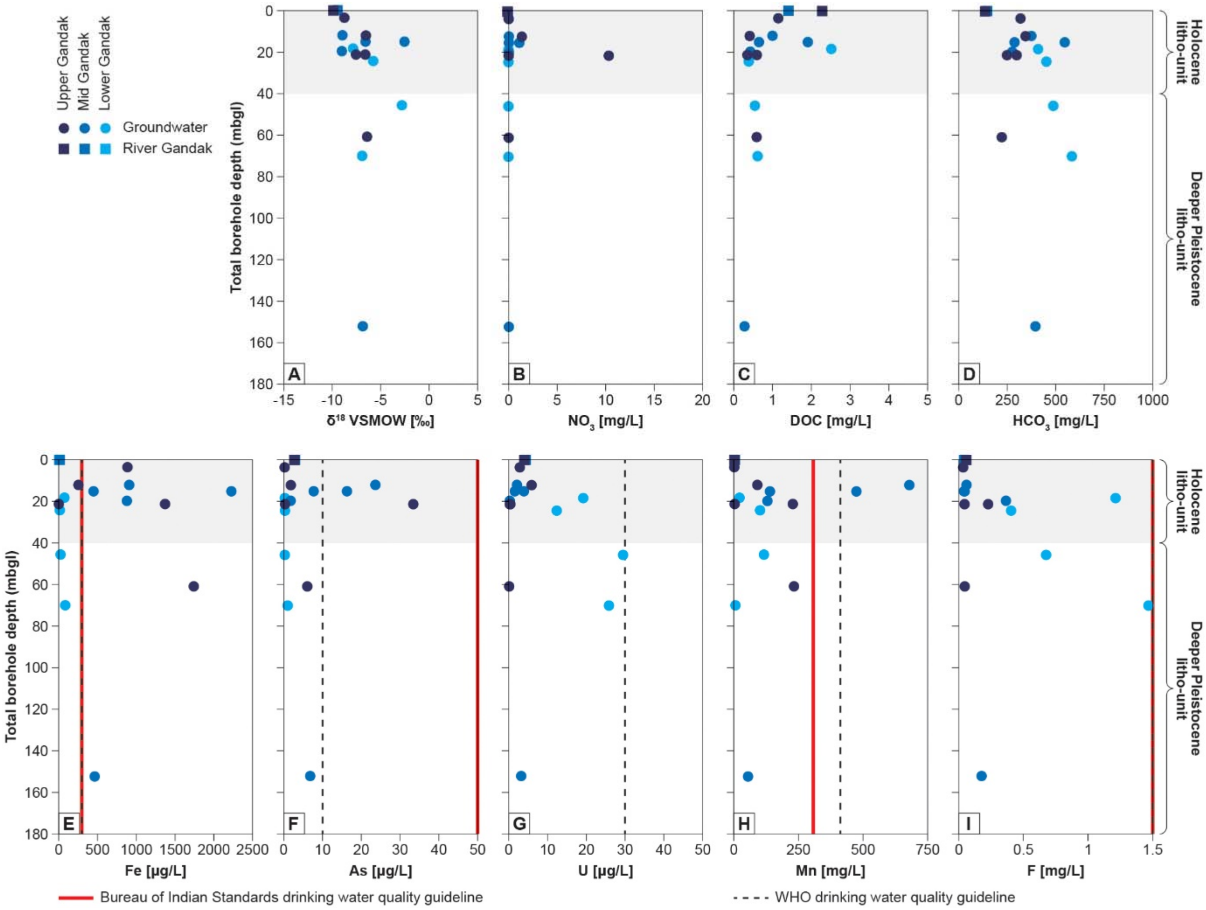


**Figure 5.** Inorganic hydrochemistry depth profiles. a) $\delta^{18}O$ VSMOW (‰), b) $NO_3$ (mg/L), c) DOC (mg/L), d) $HCO_3$ (mg/L), e) Fe (µg/L), f) As (µg/L), g) U (µg/L), h) Mn (µg/L), i) F (mg/L). e-i: India BIS drinking water guideline value shown by solid vertical line, WHO drinking water guideline value is shown by the dashed vertical line (WHO 2017).

### ***3.4 Groundwater level monitoring***

Long-term (>20 years) groundwater hydrographs for nine monitoring sites (three sites in each of the upper, mid and lower catchment zones) show shallow groundwater levels (< 10 m bgl) across the Gandak catchment (Figure 6). A distinct unimodal monsoon signal is seen at all sites, with no evidence of long-term changes in groundwater levels at any of the monitoring sites. The amplitude of seasonal groundwater level changes are comparable for the upper and mid catchment zones (typically <4 m), but larger for the lower catchment zone (typically >6 m). Groundwater levels are also deeper in the lower zone than the upper and mid zones: mean and standard deviations for monitored groundwater levels for the upper, mid and lower catchment zones were 3.5 ±1.5, 2.6 ±1.1 and 5 ± 2.1 m bgl respectively.

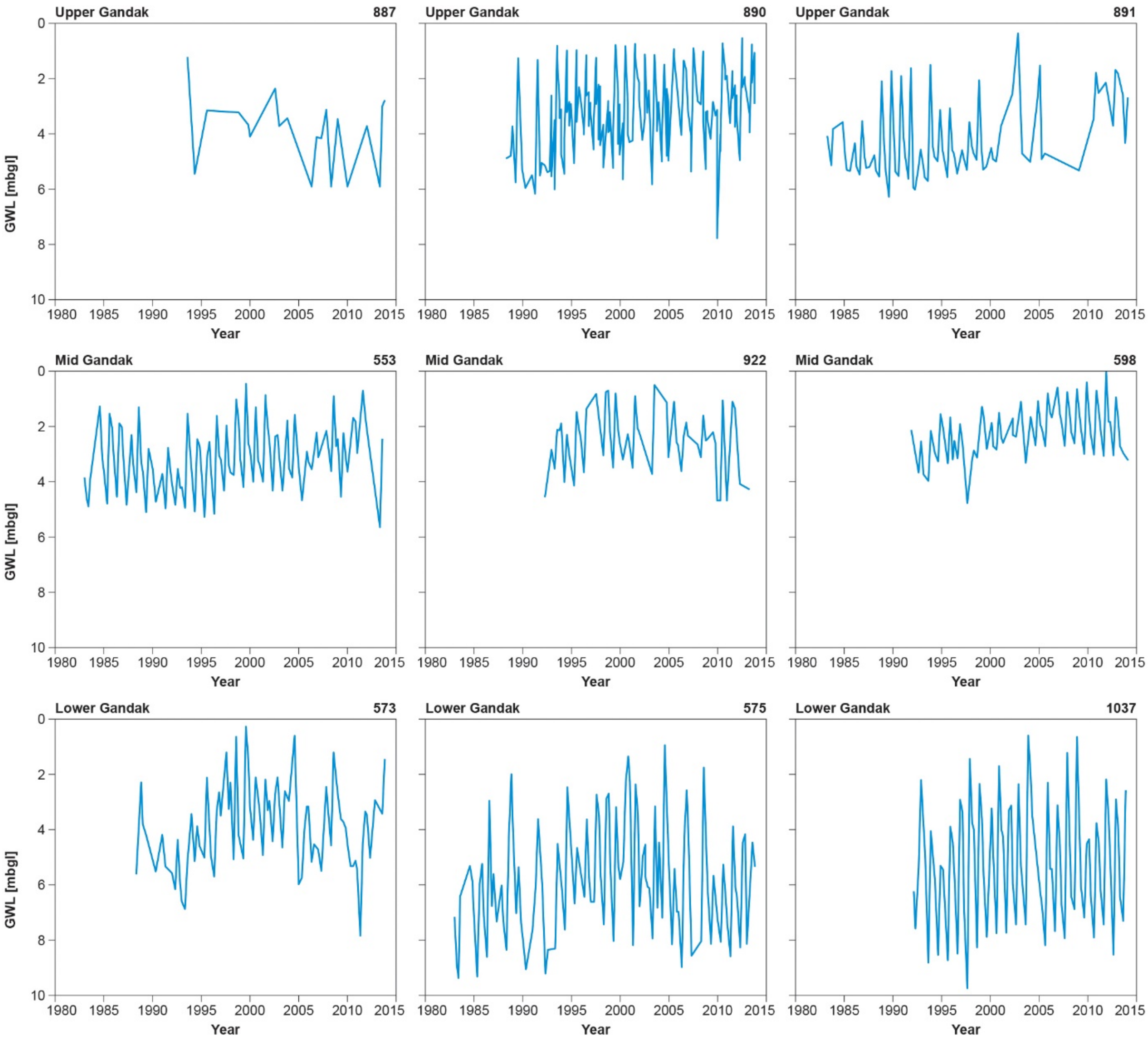


**Figure 6.** Long-term groundwater level records from the Gandak catchment (1983-2013), source MacDonald et al (2016). Borehole IDs 598 and 1037 are from the west of the River Gandak; all other hydrographs are from the east of the River Gandak. For borehole locations refer to Figure 2.

The groundwater levels time-series for the 10 shallow (<20 m) piezometers installed along the three transects are shown in Figure 7. Time-series of daily rainfall are also shown, which on average declines from north to south; mean rainfall was 5.2, 3.4 and 2.3 mm/d, for the upper mid and lower catchments, respectively, over this 22-month period. As would be expected, all groundwater levels responded to seasonal monsoon rainfall, peaking between August and September in 2017 and 2018. However, other responses can also be identified which are described below.

Considering the mid-catchment first, the groundwater level in (M4) located 480 m to the east of the Eastern Main Canal rose (by 90 cm) and then fell between January and April 2019. Given that there was no rainfall during this period, we attribute this to recharge from the canal. The level in piezometer M3, 780 m to the west of the Eastern Main Canal, between March and April 2018, was similar to that of M4, and therefore also appears to be influenced by canal recharge. The recession curves for piezometers M1 and M2, which are between 4.8 and 10 km from the Eastern Main Canal, are smoother than those near to the canal (M3, M4).

In the upper catchment, the pattern of groundwater level fluctuations in piezometers U2 and U3 between mid-March and the end of April 2018 was similar to that in boreholes M3 and M4 (Figure 7). Also, groundwater levels rise in December 2018 – January 2019, indicating that these piezometers are also responding to canal recharge or seepage. Piezometer U1 is close to the River Gandak but further from the canal; outside of the monsoon season, the groundwater levels fall rapidly and there is little evidence of a link to the canal network. This is likely due to the fact that the majority of river water is being diverted into the canal network outside of the monsoon season (Neupane et al., 2010; Choudhary et al 2012; Dixit and Shukla 2017).

In the lower catchment, the two groundwater level hydrographs follow a similar pattern to each other, with relatively linear recession curves. Recessions continue almost unbroken between the monsoons apart from a rise in the groundwater level in borehole L2, occurring over approximately one month, started just before the end of 2018. This is coincident with the rise in borehole M4, and may also be indicative of a response due to canal recharge, though this is again uncertain.

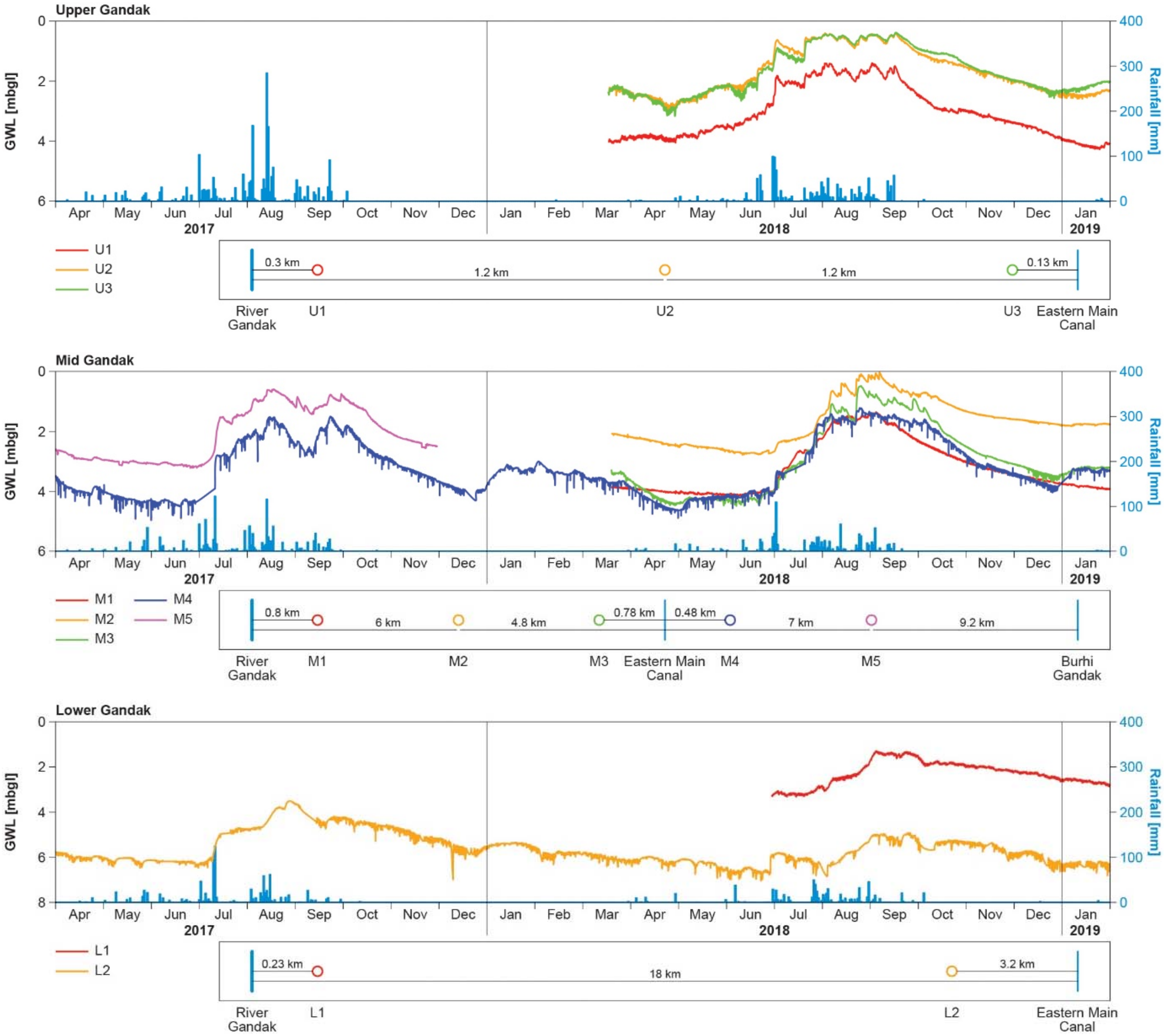


**Figure 7.** Transects of high frequency groundwater observations (2017) close to the eastern Gandak canal in the upper, mid and lower catchment zones.

### *3.5. Seasonal changes in river discharge*

River discharge decreased , at 1.85 $m^3.s^{-1}.km^{-1}$ with downstream distance from the barrage in the post-monsoon period (November 2017), when the barrage gates were open, indicating that the river was recharging the aquifer at this time. In March 2018 when all barrage gates were closed, river discharge gradually increased at approximately 0.75 $m^3.s^{-1}.km^{-1}$ moving downstream from zone 1 to 2, beyond which it was approximately stable (Figure 8). This indicated contribution of groundwater from the aquifer to the river.

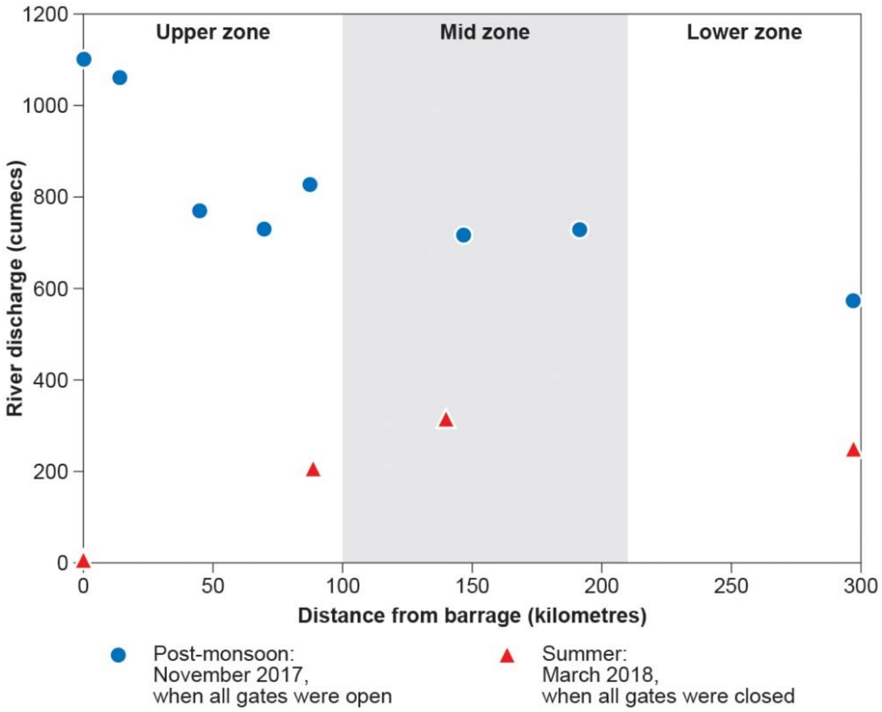


**Figure 8**. River flows downstream of Triveni barrage, during the post-monsoon (blue points: November 2017, when all gates were open) and during summer (red triangles: March 2018 when all gates were closed).

## 4. Discussion

### *4.1 Evolution in groundwater recharge and discharge across the Gandak catchment*

Evidence from stable isotope and residence time tracers can delineate changes in groundwater recharge sources across the Gandak catchment, particularly with reference to surface water and rainfall stable isotopes signatures. As with other studies (*e.g.* Lapworth et al 2015; Joshi et al., 2018) distinct isotopic signatures can often be used to differentiate between surface water and diffuse meteoric recharge sources in groundwater. Rainfall samples collected as part of this study show close agreement with data from Lapworth et al. (2015) (Figure 3a), despite being some 1000 km apart, and delineate a consistent MWL across this region of northern India (e.g. Krishan et al., 2014). The surface water (canal and River Gandak) samples in this study are significantly depleted with respect to the amount weighted rainfall value for the catchment, indicating that they originate from a higher elevation (*i.e.* the Himalayas). Canal water cannot be distinguished isotopically from the river water due to their common source in the River Gandak at the Gandak barrage (Figure 3b). The majority of groundwater samples have water stable isotope signatures that are comparable with local meteoric rainfall (Figure 3). Overall, the isotopic evidence suggests that rainfall recharge dominates across the Gandak. However, there is isotopic evidence for surface water recharge sources in shallow groundwater samples mainly from the upper and middle of the catchment. This is corroborated by the piezometer hydrographs, which show some, but limited, groundwater interaction with canals and rivers (Figure 7), and is consistent with the river discharge measurements post monsoon which indicate the river loses water downstream (Figure 8).

Baseflow to the River Gandak as the dry season progresses is shown by an increase in river discharge downstream in zones 2 and 3. With no other inflow to the Gandak or from rainfall, the increase in discharge downstream must be from groundwater. The baseflow to the river thus has a vital role in sustaining habitat for endangered gharial crocodiles (*Gavialis gangeticus*), Ganges river dolphins (*Platanista gangetica*), fresh-water turtles, fish, and other river fauna (Choudhary et al. 2012, Sinha 2018). River discharge measurements do not indicate significant baseflow in the lower catchment in zone 3. Previous modelling studies of the lower catchment confirm that the alluvial aquifer adjacent to the river is recharged by the River Gandak between May-October and January-February, but also suggest that the process is reversed during other months (Singh et al., 2018). Overall, this zone represents a system less affected by recharge from surface water due to intermittent canal flow. The deeper groundwater levels recorded in this zone (Figure 6, 7) could help account for the reduction in baseflow and will increase unsaturated zone travel times during recharge. This is reflected in the overall lower residence time tracer concentrations in shallow groundwaters in the mid and lower catchment (Figure 4).

### ***4.2 Changes in salinity across the catchment***

Most groundwater samples had higher SEC (typically > 500 μS/cm) compared to surface waters (<500 μS/cm). Salinity depth profiles (Figure 4b) show highest variability in very shallow (0-20 m bgl) groundwater samples. In contrast, shallow (0-50 m bgl) SEC concentrations were less than those recorded  in Punjab in northwest India, which is likely to be due to a combination of higher evaporation rates, more intensive groundwater pumping regimes, and potentially also greater historical use of fertilisers in Northwest India compared to the Gandak (Lapworth et al., 2017; Foster et al., 2018).

Compared to other arid settings, such as northwest India and Pakistan, the higher precipitation, lower evaporation and supply of low SEC water from surface water sources (200-300 μS/cm) in the Gandak catchment is currently adequate to maintain relatively low SEC conditions (500-1000 μS/cm) in groundwater system. Apart from a few isolated samples where there is evidence of local higher salinity surface water bodies (e.g. wetlands and oxbow lakes) impacting on groundwater, there is compelling evidence that canal leakage in the Gandak catchment results in lower SEC groundwaters close to canals compared to more distal areas where the influence of canals is limited. However, there is evidence of soil sodicity and salinity problems in the upper Gandak as a result of waterlogging (Singh and Khan 2002).

The differences in SEC depth profiles across the catchment (Figure 4) are interpreted as greater contributions of low residence time, low SEC, water from surface water sources in the upper and middle catchment compared to the lower catchment. Furthermore, the overall low SEC found across the whole Gandak catchment (typically <1000 μS/cm) contrasts with the high SEC observed with other parts of the IGB where canal irrigation is widespread but which have significantly more arid conditions than the Gandak (MacDonald et al., 2016).

### *4.3 Connection between shallow Holocene aquifer and deeper Pleistocene aquifer*

The tracer evidence (e.g. Figure 4 and 5) shows that the contribution of surface water (river or canal) sources to shallow groundwater recharge is largely restricted to the shallow Holocene aquifer (0-40 m bgl). At greater depths, in the Pleistocene aquifer, groundwater is largely consistent with more diffuse meteoric rainfall recharge, and therefore appears to be less connected hydraulically to surface water recharge sources. This is also observed in many other parts of the IGB (e.g. Joshi et al., 2018, Lapworth et al., 2015) and is consistent with the idea that the River Gandak was probably not the major source of groundwater recharge during the Holocene. The fact that this older meteoric rainfall signature in the shallow Holocene aquifer has not been overprinted in the lower catchment zone is likely to be due to relatively low groundwater abstraction as well as the limited impact of recharge from canals in this zone compared to the upper and mid catchment.

### *4.4 Conceptual Model for the Gandak River in India*

In summary, three lines of hydrochemical evidence (stable isotopes, residence time indicators and salinity) and the observations of groundwater level and river discharge from upstream to downstream confirm the hypothesis that canal leakage and river sources recharge the alluvial aquifer system, but this is largely restricted to the upper Holocene aquifer, and that the influence of canal leakage as a recharge source reduces down the catchment where canal flows are lower. The observations of higher residence time tracer concentrations, lower SEC, and more depleted water stable isotope signatures in shallow groundwater in the upper catchment compared to the mid and lower catchment (Figures 3-5), and higher SEC in both shallow and deeper aquifer layers in the lower catchment, all confirms this hypothesis. However, overall the isotopic evidence (Figure 3b) shows that meteoric rainfall sources are the dominant source of recharge across the catchment, even in the upper parts of the catchment were canal flows are higher. Dry-season groundwater baseflow helps to sustain ecological flow regimes needed for endangered species, but is reducing in the lower section of the Gandak (zone 3). Figure 9 summarises key results from this study and shows a schematic conceptual model highlighting the dominance of local meteoric recharge sources across the Gandak catchment and the evolution of recharge processes locally within the Gandak catchment due to the influence of canals and more recent groundwater pumping.

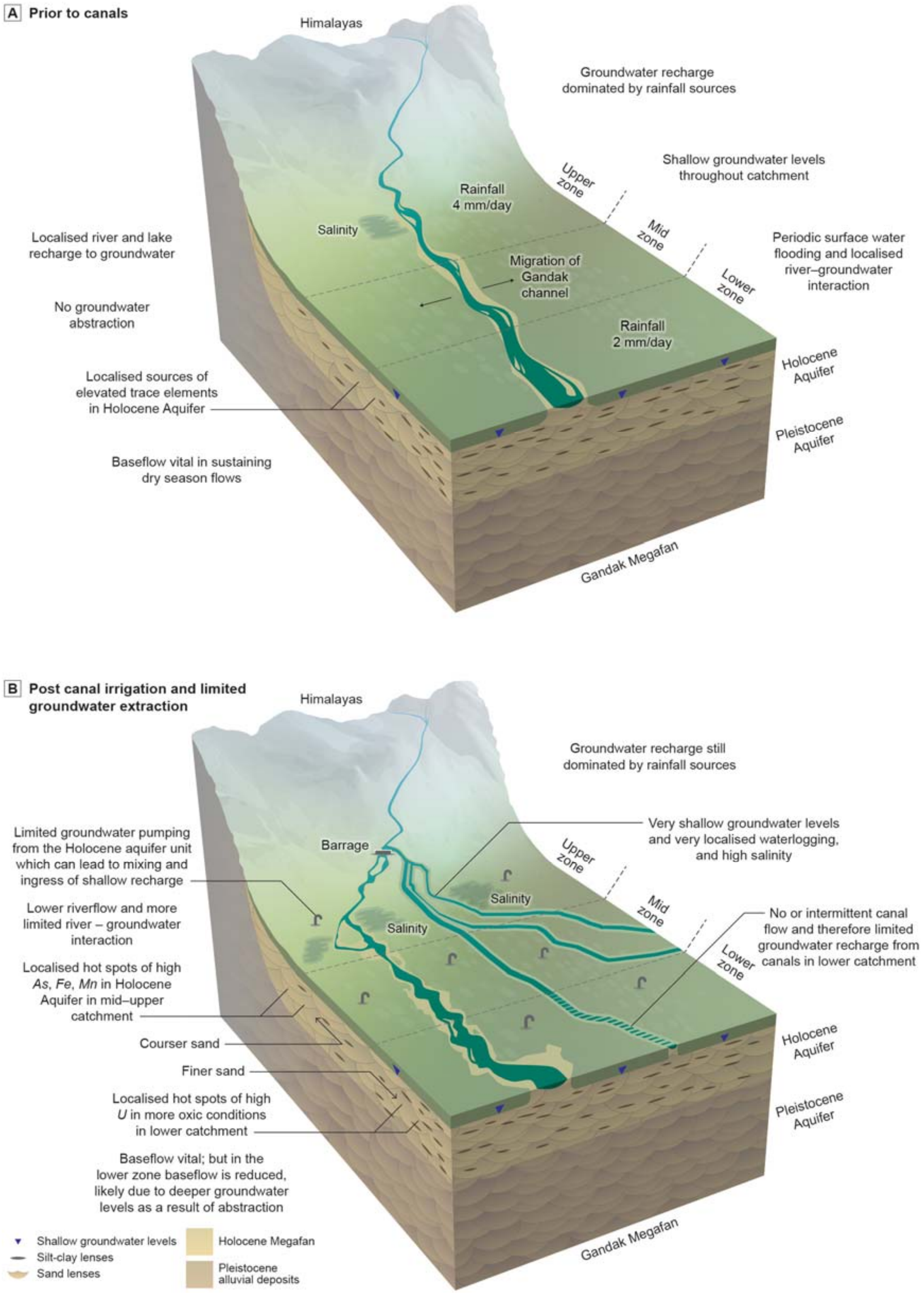


**Figure 9**. Schematic conceptual model of groundwater recharge process across the Gandak catchment a) recharge prior to canals, b) recharge and current hydrochemical conditions post canal irrigation and with limited groundwater abstraction.

***4.5 Groundwater quality constraints and controls***

Elevated arsenic, iron and manganese, above WHO drinking water guideline values, were found for a small proportion of groundwaters within the Gandak catchment (Figure 5). These exceedances were almost exclusively for groundwaters in the Holocene aquifer (<40 m bgl) with one occurrence of high iron concentration (>300 μg/L) in the deeper Pleistocene aquifer (Figure 5e). Exceedances for arsenic (n=3, 20%) were below the BIS of 50 μg/L in all cases; for manganese (n=2, 13%), the maximum concentration was 680 μg/L; and for iron (n=6, 40%), the maximum concentration was 2225 μg/L. These exceedances were only found in the upper and mid catchment, and are linked to reducing conditions in the shallow aquifer, which facilitate the reductive dissolution of iron oxyhydroxides and the release of bound arsenic (e.g. Nickson et al., 2000; BGS/DHPE 2001; Richards et al., 2020). Shallow DOC concentrations were comparable for all three catchment zones (range 0.5-2.5 mg/L), but lower concentrations (c.0.5 mg/L) are found at depth in the Pleistocene deposits across the catchment.

In contrast, uranium concentrations approaching the WHO limit of 30 μg/L were only found for groundwaters in the lower catchment, with a maximum concentration of 29.5 μg/L, not exceeding the WHO guideline value of 30 μg/L (Figure 5). The deeper groundwater levels and higher amplitude of seasonal groundwater level fluctuations in the lower catchment are likely to facilitate more oxic groundwater conditions compared to the upper and mid catchment, where groundwater levels are typically shallower with smaller seasonal fluctuations. The presence of geogenic sources of U (e.g. U minerals and iron oxide coatings on aquifer grains) is likely to be similar across the catchment. However, the prevailing oxic and alkaline conditions and carbonate complexation with U (VI) in the lower catchment zone can facilitate U mobilisation (Barnett et al., 2002; Kumar et al., 2011), and results in significantly higher U concentrations in the lower catchment compared to the other two catchment zones. These concentrations are comparable with concentrations found by Richards et al (2020), but are not as high as those detected by Lapworth et al (2017) and Coyte et al (2019) in north-west India, but aquifer redox conditions are comparable and concentrations are approaching the WHO guideline value of 30 μg/L.

Outside the Gandak catchment, high arsenic groundwater concentrations (> 50 μg/L) have been extensively reported in the mid Gangetic Basin, largely restricted to districts along the main channel of the River Ganga (Chakraborti et al., 2003, 2016; Saha 2008, 2009; Saha et al., 2010; Singh 2015; Kumar et al., 2016; Richards et al., 2020). Reductive dissolution mechanisms are inferred (Nickson et al., 2000, BGS/DPHE, 2001) from As and Fe correlations, although there is almost no reporting of DOC groundwater concentrations from this region.

Our results for spatial and depth As and U distributions within the Gandak corroborate recently published results by Richards et al (2020). Singh (2015) reports parts of three districts within the Gandak (West Champaran in the mid Gandak catchment zone and Saran and Vaishali in the lower catchment) as having arsenic concentrations > 50 μg/L, in each case at locations close to the River Gandak. Neither the results from the current study nor the majority of previously published studies, with the notable exception of a study by Jangle et al. (2016) for the Vaishali district, suggest that there is a widespread issue of high arsenic in the shallow Holocene aquifer across large parts of the Gandak catchment. Rather, the current evidence suggests that groundwater with elevated arsenic concentrations in the Gandak may be a localised phenomenon, linked to isolated hot-spots where As release from sediments within the Holocene aquifer is facilitated through reductive dissolution.

Nitrate concentrations were found to be low throughout the study catchment, most likely driven by the prevailing low oxygen groundwater conditions in the upper and mid catchment, which are likely due to the shallow groundwater levels and a limited supply of shallow sources of nitrate during recharge (e.g. Seitzinger et al., 2006). However, very low nitrate concentrations are also found in the lower catchment, where unsaturated zones are somewhat deeper, suggesting that contamination from the use of N fertilisers is less prevalent across the Gandak compared to other regions of the IGB (Agrawal et al., 1999; Lapworth et al., 2017). Groundwater salinity values found in the Gandak were low overall (typically 500-1000 μS/cm), with only isolated higher SEC due to recharge from wetlands impacted by evaporation. This reflects the relatively humid climate of the Gandak compared to elsewhere in the IGB, where shallow groundwater levels and high rates of evapotranspiration can lead to increasing groundwater salinity, which can constrain water use (MacDonald et al., 2016).

### *4.6 Potential threats to groundwater resources and endangered species*

Low groundwater abstraction, return flows, seepage from canals and high meteoric recharge in Gandak have sustained a high-quality groundwater resource throughout much of the Gandak catchment where it overlies the IGB aquifer within India. As a consequence, groundwater baseflow contributes to sustaining habitat for the endangered species in spite of flow regulation. Increased groundwater abstraction may be possible however this should proceed cautiously as recharge depends mostly on the reliability of the monsoon, and declining groundwater levels will impact environmental flows within the River Gandak. Increased abstraction may also lead to zones where the water quality is degraded, due to ingress of surface contaminants or mobilisation of in-situ contaminants and this would need to be monitored. Current groundwater salinity values across the catchment suggest that the water is suitable for irrigation. However, shallow groundwater levels are leading to localised salinity in groundwater and soil through phreatic salinization. Greater abstraction in the more waterlogged sections of the upper Gandak may be beneficial for reducing the impact of soil sodicity. However, increase groundwater use for irrigation coupled with reducing rainfall and surface water irrigation increase the likelihood of increases in groundwater salinity due to irrigation returns (Foster et al., 2018).

Increased abstraction from the deeper Pleistocene sediments is likely to lead to a mixing of shallow and deep groundwater due to the sediment architecture of the fan deposits and the lack of extensive low *K* sequences to block downward migration of groundwater. Therefore, should pumping from the deeper parts of the aquifer system increase significantly, contaminants may migrate to depth within the aquifer system.

Groundwater recharge is dominated by meteoric sources, so the largest direct threat to groundwater in the Gandak is the changing pattern of the Indian monsoon, which may impact on local rainfall and recharge. Long-term climate records show highly variability in monsoon rainfall totals (Lacombe and McCartney 2014) and future climate changes are highly uncertain.  For example, Warwade et al. (2018) report between 15-20% coefficient of variation between 1901-2002 for monsoon and annual rainfall across Bihar. Additionally, studies have noted increasing glacial melt water inflows into the River Gandak, as for many north-south flowing tributaries of the Ganga (Anand et al. 2018). However, while there have been historically no significant downward trends for rainfall totals for the lower Gandak catchment, parts of the Himalayas to the north of the study area show significant long-term reductions in precipitation (Lacombe and McCartney 2014), which may impact on surface water flows reaching the lower Gandak catchment. Increased intra-seasonal variability of the Indian monsoon has also been reported (Befort et al., 2016; Vinnarasi and Dhanya 2016). There is an indirect threat from increased abstraction, although direct recharge from irrigation canals is currently only important locally. If river flows and canal flows reduce, an increase in groundwater abstraction to meet demand would be anticipated.

Groundwater abstraction for irrigation across the Gandak catchment is largely restricted to the shallow Holocene aquifer. It is likely that this, combined with adequate recharge from canal and river water, is hydraulically restricting the downward movement of shallow recharge to greater depths within the Pleistocene aquifer, and maintaining groundwater levels. This contrasts with observations in many other parts of the IGB (Mukherjee et al 2015; Lapworth et al., 2015; MacDonald et al., 2016, Bhanja et al 2017; van Dijk et al., 2019). In addition, the availability of canal flows for irrigation for much of the year in the upper and mid Gandak catchment zones may continue to reduce the need for shallow groundwater abstraction for irrigation in these zones. Shallow groundwater levels and smaller amplitude of seasonal groundwater level fluctuations in the upper and mid zones relative to the lower catchment (Figure 6) reflect this. By contrast, in the distal lower catchment the lack of canal flows for most months of the year could lead not only to reduced recharge from canal returns, but also to increased demand for groundwater abstraction for irrigation. The lower groundwater levels in this zone (Figure 6) likely reflect the lower rainfall here than in the upper catchment and lower recharge from surface water sources, particularly canals; and perhaps a greater reliance on groundwater for irrigation.

There are no significant downward trends in groundwater levels in the Gandak catchment (Figure 6), indicating that there is adequate replenishment to the shallow groundwater system to sustain current levels of groundwater abstraction. Residence time tracer results indicate that in all parts of the catchment there is modern recharge to the Holocene aquifer, sourced from meteoric rainfall across the catchment and additionally from canal water returns in the upper and mid catchment zones, which is sufficient to sustain current groundwater demands. This is in stark contrast with the situation in other parts of the basin in Northwest India and Northern Pakistan (Lapworth et al., 2015; MacDonald et al 2016), where considerably higher historical rates of groundwater abstraction and lower average rainfall occur. Another important factor is the current more limited use of deeper groundwater resources in the Gandak compared to other parts of the IGB (Bonsor et al., 2017).

Conjunctive use of groundwater and surface-water irrigation has been a recurring emphasis of water management policymaking in the IGB aquifer (National Institute of Hydrology, 2000, Khan et al. 2014) due to problems of canal irrigation, especially with waterlogging and inefficient/erratic water supply. For the Gandak this could be encouraging farmers to shift towards more groundwater use in farm-level irrigation. However, although there is capacity for increased abstraction, groundwater and river levels and quality will need to be carefully monitored along with changes in precipitation to minimise degradation of the groundwater resource and the fragile river ecosystem which depend on baseflow.  This may, over time, accelerate the use of groundwater resources in this region in the future, as has been observed elsewhere across the IGB, which may put further pressure on groundwater resources and river ecology.

## 5. Conclusions and future outlook

Quantifying groundwater recharge sources and processes in the mid IGB and understanding ground-surface water interactions is fundamental to effective management of water resources for people and nature, and for forecasting future changes. This study contributes to ongoing debate over groundwater status across the IGB and the different anthropogenic impacts on groundwater recharge and differences in groundwater level responses observed across the IGB. This is the first assessment of groundwater residence times in the Gandak alluvial aquifer, and the first study to integrate a range of environmental tracers and groundwater level monitoring and spatially explicit river discharge measurements to conceptualise groundwater recharge process in the mid IGB. When compared with findings from other recent studies in the IGB this study highlights the heterogeneity of groundwater recharge process and groundwater level responses across the IGB. Key conclusions for the Gandak catchment are:

- Rainfall recharge sources dominate across the catchment, but stable isotope and residence time data show that groundwater recharge from canal leakage has been happening for decades, but is confined to the shallow aquifer (<40 m bgl). The shallow aquifer contains tracer concentrations indicative of active modern recharge.
- Groundwater baseflow to the River Gandak during the dry season plays a vital role in sustaining river flows, habitats, and vital aquatic ecosystems, especially for endangered species such as the gharial crocodile (*Gavialis gangeticus*) and Ganges river dolphins (*Platanista gangetica*) besides fresh-water turtles and fisheries.
- There is little evidence that the River Gandak had a major role in recharging the groundwater system throughout the Holocene aquifer system; while this process may be important locally, the dominant recharge mechanism appears to be rainfall.
- In the Holocene part of the aquifer system, groundwater chemistry is highly variable, especially for DOC, As, Mn, $NO_3$, U and other redox sensitive constituents

- There is some localised contamination from shallow geogenic sources of As in the Holocene aquifer, exceeding 10 μg/L in a few cases, but no samples in this study exceeded the BIS guideline value of 50 μg/L. Some groundwater samples showed elevated U (max = 29.5 μg/L), approaching the WHO drinking water guideline value, all from the lower catchment, where groundwater levels are generally lower.
- There is no evidence of widespread salinity build up in the areas served by irrigation canals, unlike in other more arid settings in the IGB where this is a widespread issue due to high evapotranspiration rates and shallow groundwater levels. Although there is some evidence of higher salinity in the lower Gandak catchment, where canal flows are less reliable, by contrast there is also evidence that canal water returns may reduce salinity in parts of the upper catchment.
- In the deeper Pleistocene aquifer system (>40 m bgl), groundwater chemistry shows less variation and stable isotope signatures are consistent with recharge from meteoric rainfall only, not canal or river water. Residence time tracers and stable isotope results indicate a very low proportion of modern recharge entering this system due to the fact there is currently limited groundwater abstraction from the deeper part of the aquifer.
- Our study shows that in the upper and mid catchment there is evidence of surface water recharge to the Holocene aquifer, but further away from the main canals in all catchment zones the influence of the canals reduces. There is less impact on groundwater recharge from canals in the lower catchment.

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