Journal of Hydrology 626 (2023) 130187

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Investigating groundwater recharge using hydrogen and oxygen stable isotopes in Kabul city, a semi-arid region

Mohammad Daud Hamidi [a,*], Darren R. Gröcke [a], Suneel Kumar Joshi [b], Hugh Christopher Greenwell [a]

[a] Department of Earth Sciences, Durham University, Durham DH1 3LE, United Kingdom
[b] Geo Climate Risk Solutions Pvt Ltd, Visakhapatnam, Andhra Pradesh 530048, India

ARTICLE INFO

Keywords:
Water stable isotopes
Recharge
Kabul
Groundwater
Surface and groundwater interaction

ABSTRACT

There are significant concerns about the sustainability of groundwater, and the inhabitants that depend on it, due to rapid groundwater depletion from the alluvium aquifers in Kabul city. Sustainable groundwater management in Kabul requires an understanding of the sources and rates of groundwater recharge, however, both these parameters are poorly quantified. In this study, we examined the stable isotopic composition ($\delta^{18}O$ and $\delta^{2}H$) of groundwater and surface water from the Upper Kabul River and Logar River. Utilizing the hydrograph separation approach, we assessed the percentage contribution of river water to groundwater, including the uncertainty analysis of its estimation. Our results, based on isotopic analysis, demonstrated that precipitation was the primary source of groundwater recharge in the Central Kabul sub-basin. Mixed recharge from the river, precipitation and irrigation return flow governed groundwater recharge in the Logar sub-basin. In Paghman and Lower Kabul, and Upper Kabul sub-basins, more rainfall input was observed besides the river contribution to groundwater recharge. We have noted substantial spatial and depth-related variation in the contribution of the river water to groundwater recharge. In the study area, the river water contribution (fraction contribution) to groundwater recharge has changed from over 60 ± 5 % (on average) in 2007 to less than 50 ± 5 % (on average) in 2020. We documented significant groundwater level depletion in the Central Kabul sub-basin and western parts of Kabul city (Paghman and Upper Kabul sub-basins). The present study provides important insights into the local water cycle in Kabul City, which is critical for developing sustainable management strategies for groundwater sources in this semi-arid region.

1. Introduction

More than two billion people rely on groundwater around the globe for drinking, hygiene and irrigation (Jasechko et al., 2017), with groundwater the largest reserve of freshwater currently available on the planet (Opie et al., 2020). Groundwater constitutes the primary source of drinking water in semi-arid and arid regions, it is an essential component of the water cycle in alluvial aquifer systems where the depletion of groundwater is a major issue and surface water often recharges groundwater (Alley et al., 2002; Gleeson et al., 2015). Therefore, for water management, it is important to understand the spatio-temporal interactions between surface and groundwater, mainly at an appropriate local and regional scale (Joshi et al., 2018).

Approximately 4.4 million people residing in the Kabul city region rely on groundwater as a primary source of drinking water (Broshears et al., 2005; Hossaini, 2019). Located within the Hindu Kush Himalayan region, Kabul City has undergone rapid unplanned urbanization, increasing water demand over the past 20 years (Noori and Singh, 2021; Zaryab et al., 2022b). Meldebekova et al. (2020) observed 5.3 cm/year subsidence in the land surface above the Upper Kabul aquifer, which was highly correlated to groundwater level decrease. Based on the Representative Concentration Pathway (RCP 4.5) climate model, projections indicate a decline in winter precipitation in the Kabul River Basin between 2020 and 2079 (Ghulami et al., 2022). Landsat-based analysis of glacier lakes in Hindu Kush Himalaya, including Afghanistan, indicates the trend is decreasing (Maharjan et al., 2018). Surface runoff modelling projections for Afghanistan suggest a 20 % to 30 % decrease from 2041 to 2060 due to climate change (Milly et al., 2005). Furthermore, surface runoff modelling for the Upper Kabul River estimates a 4.2 % decrease by 2030 due to climate impact under RCP 4.5 (Akhtar et al., 2021).

* Corresponding author.
E-mail address: mohammad.d.hamidi@durham.ac.uk (M.D. Hamidi).

https://doi.org/10.1016/j.jhydrol.2023.130187

Available online 18 September 2023

Monitoring the groundwater levels in the drinking water wells network between 2004 and 2016 revealed a rapid decline in groundwater levels in Kabul City (Brati et al., 2019; Hamidi et al., 2023; Mack et al., 2013; Noori and Singh, 2021; Saffi, 2019, 2014, 2011). Observations of river flow and nearby groundwater wells estimated that the majority of groundwater recharge takes place from October to May (Sadid, 2020). Moreover, Masoom (2018) suggested artificial groundwater recharge from excess Kabul River flow during the rainy season could be used as a sustainable management approach for the basin. Geographic Information System (GIS) and remote sensing data have been utilized to assess groundwater recharging zones and indicate excellent potential for groundwater recharge in Kabul City (Hussaini et al., 2022; Mahdawi et al., 2022; Nasir et al., 2021; Singh and Noori, 2022). However, there remains limited understanding of groundwater sources, the interaction between surface and groundwater, and recharge processes in the Kabul city region.

Stable isotopes of hydrogen and oxygen (δ^2H and $\delta^{18}O$) contained in water molecules serve as natural tracers for quantifying groundwater recharge dynamics and sources (Clark and Fritz, 1997; Jasechko, 2019; Joshi et al., 2018; Kumar et al., 2021) and understanding the interaction between surface water and groundwater (Davisson et al., 1999; Jasechko, 2019; Xie et al., 2022). Isotopic values such as $\delta^{18}O$ and δ^2H follow predictable patterns in natural systems, and are influenced by atmospheric, geological, and biological processes (Clark, 2015; Gat, 1996; Rai et al., 2021). Changes in $\delta^{18}O$ and δ^2H values primarily occur due to due to phase changes, mixing, and temperature variations (Clark and Fritz, 1997; Jeelani et al., 2013; Keesari et al., 2017; Scheihing et al., 2017). High-temperature water–rock interactions increase $\delta^{18}O$ values, while low-temperature interactions decrease $\delta^{18}O$ values, resulting in lower or higher d-excess values, respectively (Giggenbach, 1992; Kloppmann et al., 2002). Factors such as high-temperature alterations of the parent groundwater and evaporation prior to or during infiltration contribute to the enrichment of isotopic values (Giggenbach, 1992; Jasechko, 2019). Groundwater samples with higher $\delta^{18}O$ and δ^2H values than amount-weighted precipitation indicate recharge by local precipitation modified by evaporation (Joshi et al., 2018). A low intercept value suggests that groundwater may be affected by evaporation or mixed with evaporated water (Bowen et al., 2018). Furthermore, partial evaporation increases both δ^2H and $\delta^{18}O$ along $\delta^2H/\delta^{18}O$ slope, leading to low deuterium excess values. Under conditions of low humidity and soil evaporation, the slopes of $\delta^2H/\delta^{18}O$ typically exhibit lower values (Giggenbach, 1992). The isotopic values, along with their characteristics and relationships, serve as valuable tools for inferring the physical processes at play within water systems.

The only study hitherto on stable isotopes of groundwater in the Kabul city region was conducted between 2004 and 2007 (Mack et al., 2010). Their intriguing conclusion was that no groundwater samples indicated substantial evaporation in this arid basin. Due to a lack of historical isotopic data of groundwater and surface water, Mack et al. (2010) could not investigate the long-term change in the isotopic signature of the groundwater. To our knowledge, no attempt has taken place since 2007 to investigate the spatio-temporal characteristics of δ^2H and $\delta^{18}O$ in groundwater in the alluvial aquifer systems in the Kabul city region. In this study, we focus on the δ^2H and $\delta^{18}O$ analysis of surface water and groundwater samples and groundwater level dynamics between 2007 and 2020 to understand groundwater recharge sources. The primary objectives of this study to investigate the Kabul city region encompass: (1) understanding of groundwater recharge processes; (2) understanding the interaction between surface water and groundwater; and (3) understanding groundwater dynamics in the aquifer system.

2. Study area

The study covers 450 km^2 of the Kabul city area with a population of 4.4 million (NISA, 2020). The elevation of the city is 1800 m above mean sea level (Favre and Kamal, 2004). Kabul's climate is semi-arid, with more than 300 mm of average annual rainfall and evapotranspiration is 1600 mm, annually (Zaryab et al., 2017). Low rainfall and a high evaporation rate significantly impact surface water and groundwater storage, water quality, and community health (Sheikhi et al., 2020). The average minimum daily air temperature between 2000 and 2020 was –15.6 °C and the average maximum daily air temperature was 27.8 °C, (POWER-Project, 2022). Kabul city has four sub-basins, and the city lies at the intersection of the Kabul River (Upper Kabul River and Lower Kabul River), Logar River, and Paghman River (Fig. 1). In the west of the city, the Paghman River joins the Kabul River near the Deh Mazang area and then flows east toward its confluence with the Logar River (Saffi, 2019). The geology of Kabul city is formed due to plate movements during the Late Palaeocene period, and is located in the Kabul Block. Kabul City is surrounded by Precambrian metamorphic rocks such as gneisses, amphibolites, schists, quartzite, and marbles (Bohannon, 2010). It also contains some younger limestone and marl in the southern and eastern margins (Bohannon, 2010; Lindsay et al., 2005). The basin is filled with consolidated and unconsolidated sediments consisting of clay, sand, gravel, pebbles, and conglomerates, which belong to the Quaternary and the late Tertiary (Neogene) periods (see Fig. S1 for lithology of deep boreholes in Kabul). The thickness of Neogene sediments ranges from 30 to 600 m (JICA, 2011). The recharge primarily occurs from river beds and irrigation channels when the rivers experience high peak flows. However, these recharge mechanisms are not well documented (Broshears et al., 2005; Zaryab et al., 2017). The aquifers in the Kabul Basin are categorized into two primary types: the shallow Quaternary aquifer and the deep Neogene aquifer (Böckh, 1971). The shallow aquifer can be further classified into four aquifers, primarily belonging to the Quaternary period (Böckh, 1971; Broshears et al., 2005; JICA, 2011).

3. Methods

3.1. Data sources

Historical isotope data consisted of 21 groundwater and 3 surface water sampling points located in the study area: these were collected between December 2006 to mid-July 2007, as described by Mack et al. (2010). As part of this study, groundwater samples for isotopic analyses were collected in January 2020 from 41 piezometric wells and 2 samples from rivers in the study area (Fig. 1). It is important to note that water levels were accurately recorded in all piezometers before the sampling to compare the static water level with historic data. The depth to the water level in sampled wells ranged from 2 to 90 m below ground level (m bgl) in the study area.

For groundwater sampling, the piezometers were purged for more than 30 min prior to sampling for each location (enough to replace the whole volume twice), and duplicates were collected from each location in 50 ml sterile Falcon centrifuge tubes. The collected water samples were transported by air in polystyrene containers to the UK and subsequently stored in a refrigerator, until isotopic analysis could be performed in the Stable Isotope Biogeochemistry Laboratory (SIBL) at Durham University.

3.2. Water δ^2H and $\delta^{18}O$ analyses

Stable isotope analysis of water was performed after filtering the water at 0.25 μm, using a Los Gatos Liquid-Water Isotope Analyzer (LWIA) DLT-100. Each water sample was analysed 10 times but the first 3 injections were discarded due to memory effects. All analyses were then processed using LWIA software to achieve higher precision using the remaining 7 injected samples. IsoAnalytical water standards (see supplementary material) were analysed as a group with separated by deionised water samples. The same analytical procedure was performed on the standards, and each group of standards was analysed every 8

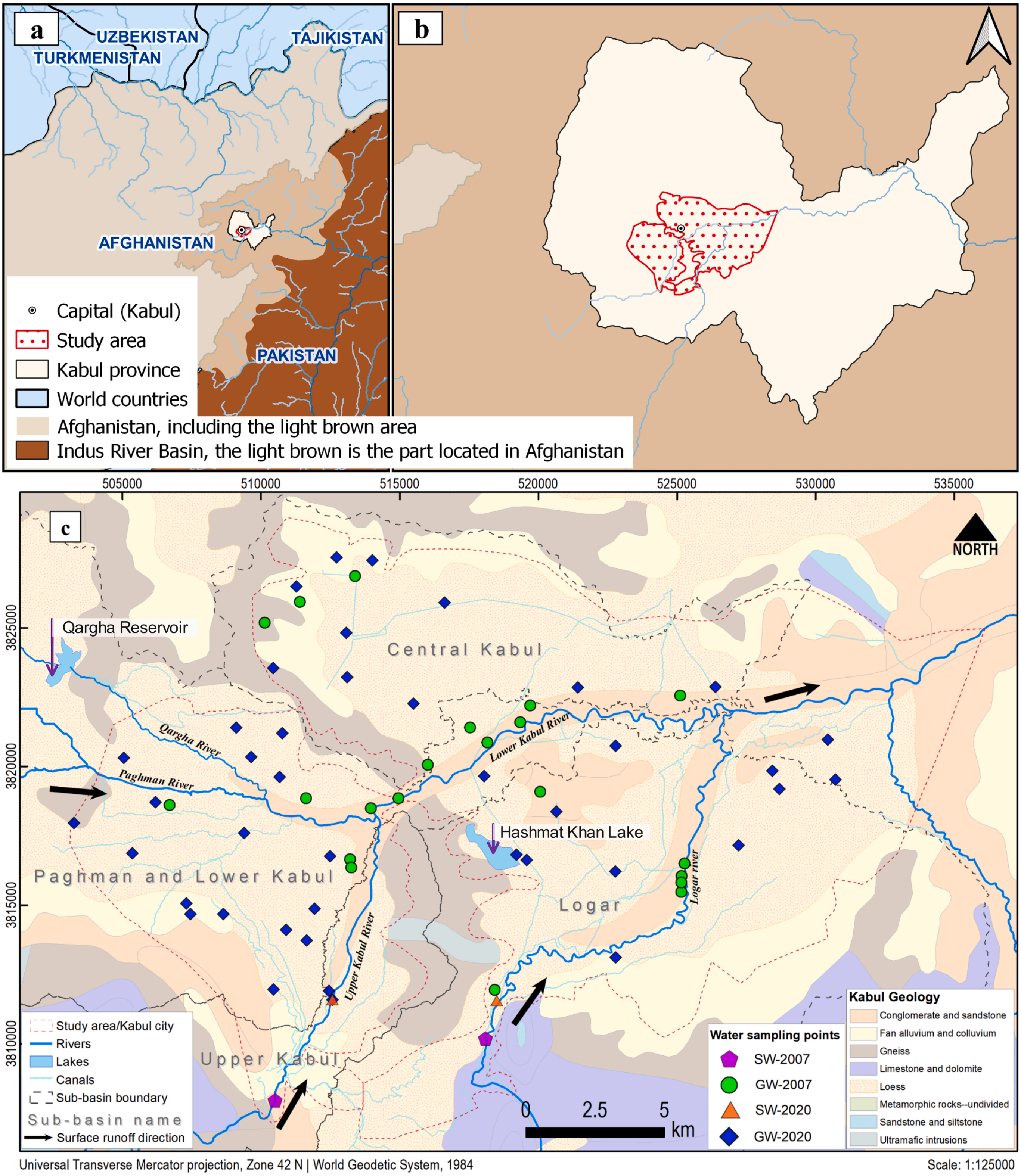

Fig. 1. Map of countries sharing Indus River Basin (a), location of the study area in larger Indus River Basin (b), and spatial distribution of water sampling locations superimposed on geological settings of the study area (c). The pentagons and triangles show surface water sampling locations, and circles and diamonds show groundwater sampling locations for 2007 and 2022, respectively. Data source: Geology from Bohannon and Turner (2007), Lindsay et al. (2005). Sample locations for 2007 (Mack et al., 2010).

samples. The results are expressed in standard delta (δ) notation as per mil (‰) values in relation to VSMOW or Vienna Standard Mean Ocean Water (Sharp, 2017). The average standard deviation for the samples was < 0.4 ‰ (1 s) for δ^2H, and < 0.2 ‰ (1 s) for δ^{18}O.

In order to investigate the recharge process and groundwater dynamics we calculated deuterium excess (d-excess) values of the river (surface water) and groundwater samples. The d-excess was calculated following Dansgaard (1964): d-excess = $\delta^2H - 8 \times \delta^{18}O$. D-excess is a key parameter for tracking the impact of evaporation on the isotopic composition of precipitated water before groundwater recharge (Clark and Fritz, 1997). Fluctuations in d-excess depend on relative humidity and evaporation in precipitation, as well as the change in wind speed and ocean surface temperature (Clark and Fritz, 1997; Gat, 1983). The global mean value of d-excess is + 10 ‰, indicating 85 % relative humidity (Clark and Fritz, 1997; Merlivat and Jouzel, 1979).

3.3. Two-component mixing model

In order to evaluate the contribution of surface water (i.e., river water) to groundwater recharge in the study area, where the groundwater is considered to be a mixture of only two end-members (i.e., river and precipitation), a tracer-based two-component mixing model was employed (Clark, 2015; Clark and Fritz, 1997). In the tracer-based study, many researchers have used δ^2H and δ^{18}O values of water from three different sources - including Herrmann and Stichler (1980); and Joshi et al. (2018). Following Rai et al. (2021) and Joshi et al., (2018), the present study uses δ^{18}O values of groundwater, surface water (river water), and precipitation (amount weighted average precipitation, or AWAP) to explore the surface water and groundwater interaction. The fraction of groundwater due to river water is calculated using Eq. (1):

$$f_r = \frac{(C_g - C_p)}{(C_r - C_p)} \tag{1}$$

Where C_r is the δ^{18}O value of river water, C_g is the δ^{18}O value of groundwater, C_p is the δ^{18}O value of precipitation (AWAP), and f_r is the contribution of river water to groundwater.

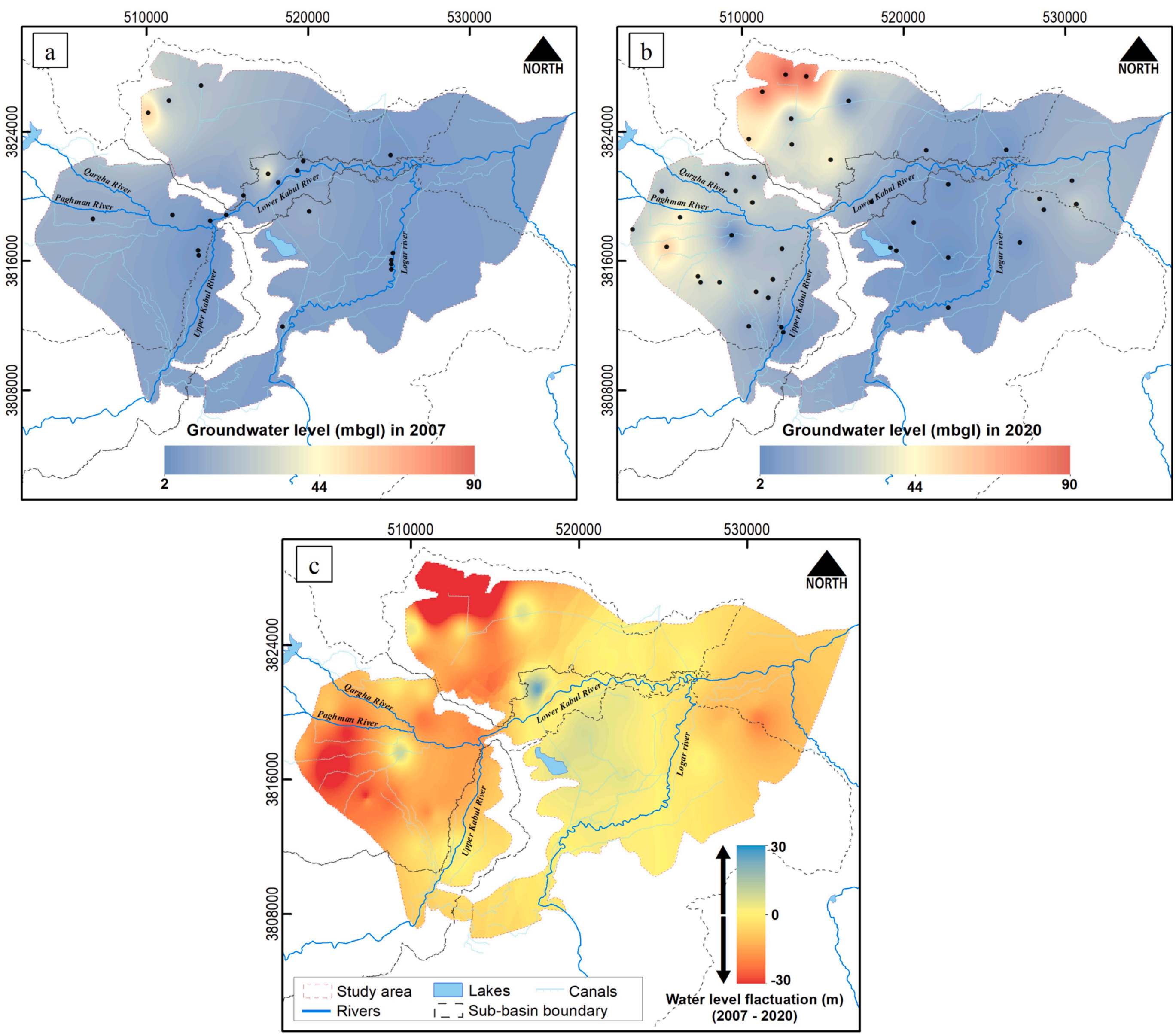

Fig. 2. Spatial distribution of depth to water level maps: (a) 2007; (b) 2020; and (c) the groundwater level difference between 2007 and 2020. The black points in (a) and (b) are sampling locations.

3.4. Uncertainty analysis

The first-order Gaussian error propagation method was employed following Uhlenbrook and Hoeg (2003) and Genereux (1998) to evaluate uncertainty in the two-component mixing model. The measurement errors in $\delta^{18}O$ values of surface water, groundwater, and precipitation were ± 0.4 ‰. The uncertainty was calculated using the following equation:

$$W_y = \sqrt{\left(\frac{\partial y}{\partial c_1}W_{c1}\right)^2 + \left(\frac{\partial y}{\partial c_2}W_{c2}\right)^2 + \cdots + \left(\frac{\partial y}{\partial c_n}W_{cn}\right)^2} \quad (2)$$

Where:
W: uncertainty in the contribution of a specific end member,
$c_1, c_2 \cdots c_3$: variables,
$W_{c1}, W_{c2} \cdots W_{cn}$: measurement error in each variable, and.
$\frac{\partial y}{\partial c_1}, \frac{\partial y}{\partial c_2} \cdots \frac{\partial y}{\partial c_n}$: partial differentiation of factor equations for each variable in the two-component mixing model.

4. Results and discussion

4.1. Spatio-temporal patterns of groundwater level

The spatio-temporal distribution of groundwater level maps for 2007 and 2020 were prepared to understand the groundwater system of Kabul City. We used an inverse distance weighting (IDW) interpolation algorithm in ArcGIS (Esri, 2019) to generate the groundwater level map. Fig. 2a and 2b demonstrate the spatial distribution of groundwater levels for 2007 and 2020, respectively. The spatial distribution of the groundwater level shows marked variation across Kabul City. The groundwater level in 2007 varied between 3.2 and 57.5 m bgl. However, the range of groundwater levels has drastically changed to lie between 2.7 and 90.1 m bgl at the time of this present study (i.e., 2020), indicating a combination of declining and rising trends across different locations in groundwater levels of the study area. Shallow groundwater levels (<25 m) were observed in most of the study area (except for two locations in the Central Kabul sub-basin) in 2007 (Fig. 2a). In 2020, the groundwater level map shows a deeper level (>35 m) in the Central Kabul and Paghman sub-basins (Fig. 2b) compared to 2007. In contrast, shallow groundwater levels in parts of the Lower Kabul and Logar sub-basins exhibited minimal drawdown between 2007 and 2020. In order to demonstrate the changes in groundwater levels, the water table fluctuation map was generated based on the difference between 2007 and 2020 groundwater level data (Fig. 2c). It highlights that the Kabul central basin experienced a water depletion ranging from 35 to 55 m during this period. Similarly, the range of depletion in western parts of Kabul city (Paghman and Upper-Kabul sub-basins) was between 15 and 35 m. Groundwater depletion in parts of Kabul city is linked to population growth, rapid unplanned urbanization that has led to overutilisation of groundwater (Jawadi et al., 2020; Noori and Singh, 2021; Zaryab et al., 2022a), and changes in landcover. For instance, between 2005 and 2020, the built-up area in Kabul City increased from 15.3 % to 31.9% while the agriculture area decreased from 17.1 % to 14.8 % (Noori and Singh, 2021).

The water table fluctuation (WTF) method was employed to estimate the groundwater storage change rate in the study area, Eq. (3):

$$R = S_y \Delta h / \Delta t \quad (3)$$

Where Sy is the specific yield, and $\Delta h/\Delta t$ is the water table fluctuation over time (Beg et al., 2022; Bhanja et al., 2019; Healy and Cook, 2002). The specific yield values were adapted from Sadid (2020), and the spatial distribution of map specific yield was produced for Kabul City (Fig. S2).

The spatial distribution of the groundwater storage change rate was estimated based on the WTF approach (Fig. 3). Spatially, the amount of water rising rate in the Logar and lower Kabul sub-basins were the highest (approximately 0.25 m/year). The Central Kabul sub-basin had the highest water declining rate in the study area, while Paghman and

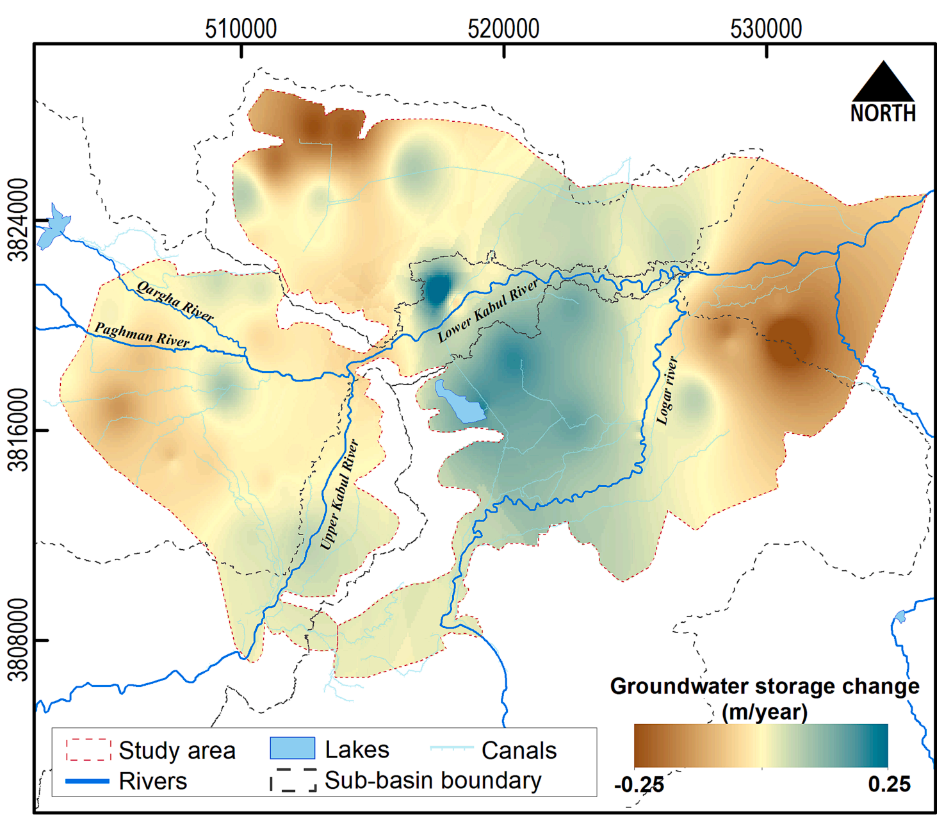

Fig. 3. Groundwater storage change rate of Kabul city region.

Lower Kabul sub-basin illustrated a mixed trend of rising and declining rates of groundwater storage change. The considerable variability in groundwater storage rates was mainly associated with the aquifer properties and infiltration rate. The positive rates in the Logar region indicated a rising trend in groundwater storage rate between 2007 and 2020, suggesting that the groundwater is being replenished due to excess surface water available for infiltration from the Logar River.

4.2. Isotopic characterization of precipitation, surface water and groundwater

a. Precipitation.

In order to understand the dynamics of δ^2H and δ^{18}O values for precipitation (i.e., the dominant water source), we use the data from the Karizimir station located at Kabul International Airport. The isotopic composition of precipitation was measured between January 1962 to September 1989 by the International Atomic Energy Agency (IAEA/WMO, 2022). The δ^2H value of precipitation varies from −103.0 ‰ to + 33.0 ‰ (mean: –33.2 ‰ ± 7.2 ‰, $n = 86$), δ^{18}O from −16.0 ‰ to + 3.5 ‰ (mean: −6.0 ‰ ± 1.0 ‰, $n = 86$), and d-excess from −9.7 ‰ to + 40.6 ‰ (mean: +14.6 ‰ ± 3.7 ‰, $n = 86$). The isotopic and d-excess values of precipitation, showing a wide range in the study region, can be attributed to the westerly moisture source for precipitation. In addition, following Clark and Fritz (1997) and Hughes and Crawford (2012), AWAP isotopic values have been estimated for IAEA precipitation data in Kabul utilizing isotopic values of individual events using Eq. (4):

$$AWAP\,(\delta_w) = \sum_{1}^{n} \delta_i P_i \Big/ \sum_{1}^{n} P_i \qquad (4)$$

Where δ_i is the isotopic value of an individual event with a precipitation amount of P_i. The AWAP values of δ^2H and δ^{18}O were (-36.0 ‰ ± 8.5 ‰) and (-7.15 ‰ ± 1.13 ‰), respectively.

A cross-plot between δ^2H and δ^{18}O values is shown in Fig. 4. The regression line in Fig. 4 represents the local meteoric water line (LMWL): $\delta^2\text{H} = 7.33 \times \delta^{18}\text{O} + 12.37$. We compared LMWL with the global meteoric water line or GMWL: $\delta^2\text{H} = 7.91 \times \delta^{18}\text{O} + 8.72$, defined by Terzer et al., (2013). The slope in LMWL is less than the GMWL, indicating isotopic enrichment during the precipitation event. This enrichment occurs due to evaporation processes which alter the isotopic composition of precipitation, and possibly due to regional factors such as air mass source (Li et al., 2022). In comparison, the intercept value of LMWL is higher than the GMWL, which is directly related to the evaporation rate of the local precipitation (Clark, 2015). This can be attributed to higher contribution of local air masses through evapotranspiration occurring at lower temperatures, in line with similar observations in the western-Himalayan region by Kumar et al. (2010), or contribution from western disturbances (Zhou and Li, 2018).

b. Surface water.

The δ^{18}O, δ^2H and d-excess values of the water from the Logar and Upper Kabul rivers in the study area for 2007 and 2020 are presented in Table 1 (see Fig. 1 for spatial location of Logar and Upper Kabul Rivers). The range in river water δ^{18}O in 2007 was between −9.2 ‰ to −9.0 ‰, whereas in 2020 it ranged between −8.3 ‰ and −8.1 ‰. Similarly, the range in river water δ^2H in 2007 was between −61.5 ‰ to −54.3 ‰, whereas in 2020 it ranged between −52.4 ‰ to −46.1 ‰. Between 2007 and 2020, the river water d-excess decreased 1.5 ‰, on average.

The difference in isotopic composition (on average δ^{18}O = -0.23 ‰, δ^2H = -6.79 ‰, d-excess = +4.95 ‰) between the Logar and Upper Kabul basin river waters could potentially be due to the distance travelled and the larger catchment area of Logar sub-basin compared to Upper Kabul sub-basin. The distance travelled can affect the isotopic composition of water by evaporation, particularly in this semi-arid region. For example, surface water observations in California showed −21 ‰ distance-related depletion in δ^2H for every 100 km of river (Williams and Rodoni, 1997). The Logar River consists of 6 tributaries, before entering Kabul city and the flow distance from upstream is approximately 250 km. The Upper Kabul River consists of 3 tributaries before entering Kabul city and the flow distance from upstream is approximately 100 km. The water from the Logar River is used for irrigation in the upstream region before entering Kabul City (Sadid, 2020).

Table 1
Average river water δ^{18}O, δ^2H, and d-excess between 2007 and 2020.

River	2007 δ^{18}O (‰)	δ^2H (‰)	d-excess	2020 δ^{18}O (‰)	δ^2H (‰)	d-excess
Logar	−9.2	−61.5	+12.4	−8.3	−52.4	+14.1
Upper Kabul	−9.0	−54.3	+17.5	−8.1	−46.1	+18.8

Note: The data source for 2007 (Mack et al., 2010).

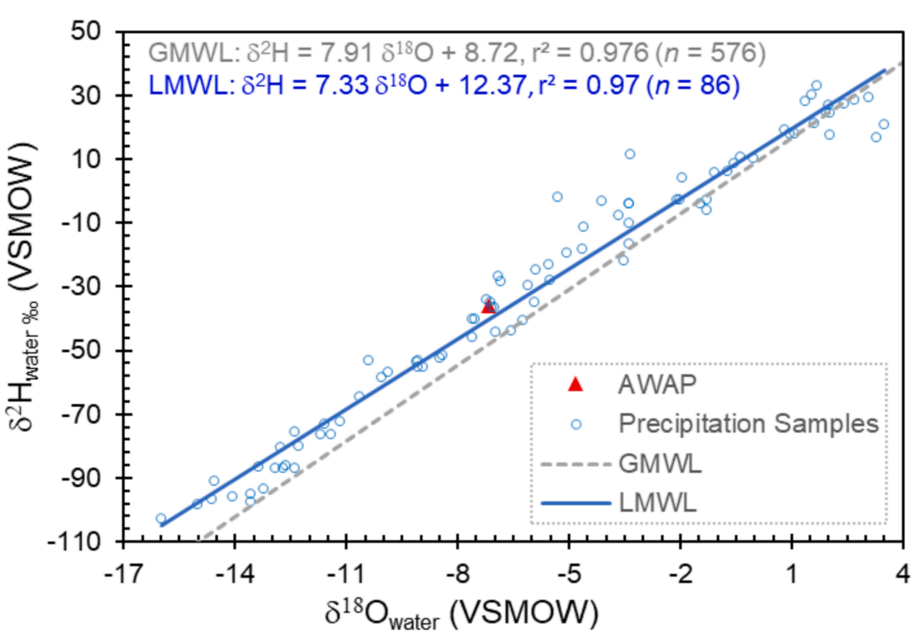

Fig. 4. Cross plot between δ^2H and δ^{18}O values of precipitation. Data source: Precipitation data from (IAEA/WMO, 2022).

Furthermore, the isotopic composition of the Logar River samples shows depleted values relative to the AWAP in 2007 and 2020. Similarly, the isotopic composition of the Upper Kabul River shows depleted values relative to the AWAP and values fell on LMWL in 2007 and above LMWL in 2020. This can be attributed to the different sources of water contributing to the river water, such as higher altitude water (snow/sleet), and/or precipitation (Rai et al., 2009; Semwal et al., 2020).

In order to better understand the enrichment in the isotopic composition of river water, we used hydrometeorological datasets from 2000 to 2020. Precipitation and temperature variation in Kabul are utilized to explore the reason behind the variation in isotopic characteristics of surface water between 2007 and 2020. Fig. 5a illustrates historical daily precipitation and temperature data from 2000 to 2020 for Kabul City, obtained from the NASA Langley Research Center (POWER-Project, 2022). Kabul City has periodically experienced dry years (Baig et al., 2020). Fig. 5a highlights, on average, the amount of precipitation was very low between 2000 and 2005 (average annual rainfall $\leq$ 200 mm), while an increase was observed in the average amount of precipitation between 2006 and 2016 (average annual rainfall $\geq$ 320 mm). The city experienced extreme drought in 2018, while the average precipitation significantly increased in 2020. These temporal changes in temperature and precipitation contribute to and impact the isotopic characteristics of surface water. Fig. 5b - c illustrate the precipitation and temperature before the river water sampling campaigns in 2007 and 2020.

The total amount of precipitation in December 2006 was 74.88 mm with an average temperature of −1.8 °C; the total amount of precipitation in January 2007 was 9.44 mm with an average temperature of −0.3 °C (Fig. 5b). However, in 2020 December was warmer with an average temperature of 2.7 °C, and significantly less precipitation (9.2 mm) than in December 2006. January 2020 was colder with a temperature average of −4.1 °C and significantly higher precipitation (51.5 mm) in comparison to January 2007 (Fig. 5c). Thus, the lower amount of rain and higher temperature in January 2007, compared to the higher amounts of rain and lower temperature in January 2020 illustrates the enrichment is due to difference in source such as precipitation or snow/sleet and/or secondary evaporation, similar to observations in western Himalayan region by Jeelani et al. (2013). The relationship between mean $\delta^{18}O$ values and monthly precipitation amount in the study area is weak and negative (Fig. S3). The negative correlation between the mean $\delta^{18}O$ values and monthly precipitation amount, known as the amount effect, diminishes in higher latitude regions or may even exhibit a weak positive correlation (Clark, 2015; Sharp, 2017).

c. Groundwater.

The isotopic composition of groundwater in Kabul city for δ^2H varied from −64.5 ‰ to −32.3 ‰ (mean: −49.3‰ ± 7.2 ‰, $n = 62$), $\delta^{18}O$ from −9.6 ‰ to −4.9 ‰ (mean: −7.9 ‰ ± 1 ‰, $n = 62$), and d-excess from + 5.3 ‰ to + 24.4 ‰ (mean: 14.2 ‰ ± 3.6 ‰, $n = 62$). The average

Table 2
Analysis results of groundwater samples for $\delta^{18}O$, δ^2H, and d-excess in 2007 and 2020.

Sub-basin	2007 $\delta^{18}O$ (‰)	δ^2H (‰)	d-excess	2020 $\delta^{18}O$ (‰)	δ^2H (‰)	d-excess
Central Kabul	−9.2 ($n = 4$)	−60.5 ($n = 4$)	+13.2 ($n = 4$)	−8.2 ($n = 10$)	−48.9 ($n = 10$)	+17.0 ($n = 10$)
Logar	−8.5 ($n = 6$)	−56.5 ($n = 6$)	+11.6 ($n = 6$)	−7.1 ($n = 12$)	−44.8 ($n = 12$)	+12.2 ($n = 12$)
Paghman and Lower Kabul	−8.8 ($n = 11$)	−55.4 ($n = 11$)	+14.8 ($n = 11$)	−7.4 ($n = 17$)	−44.3 ($n = 17$)	+14.7 ($n = 17$)
Upper Kabul				−7.1 ($n = 2$)	−43.0 ($n = 2$)	+13.7 ($n = 2$)

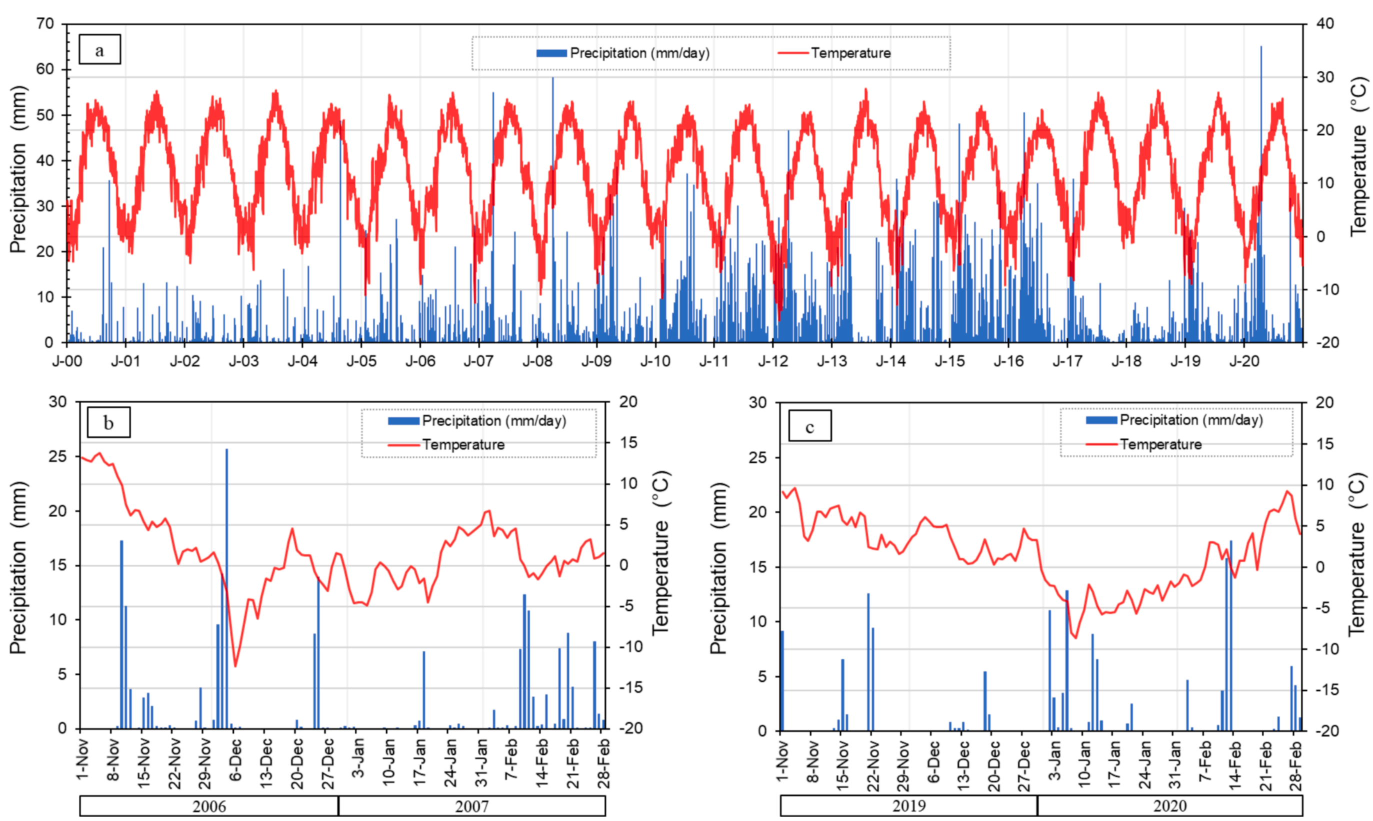

Fig. 5. Precipitation and temperature trends in Kabul city: 2000 – 2021 (a), November 2006 to February 2007 (b), and November 2019 to February 2020 (c). *Data source*: NASA's POWER-Project.

groundwater $\delta^{18}O$, δ^2H and d-excess values in the study area for 2007 and 2020 are presented in Table 2. Central Kabul is the only sub-basin in Kabul City without a river running through it. Compared to the other sub-basins in Kabul City, the lack of direct river water infiltration may explain the overall lower values of $\delta^{18}O$ in the groundwater of the Central Kabul sub-basin both in 2007 and 2020.

Overall, the data presented in Table 2, illustrate that the groundwater samples are elevated in $\delta^{18}O$, δ^2H and d-excess values in 2020 compared to 2007. Fig. 6 illustrates the cross plots of $\delta^{18}O$ and δ^2H of the groundwater samples from all sub-basins in the study area, including groundwater lines (GWL). Fig. 6a highlights that the groundwater samples for 2007 fall below the LMWL, while in 2020, besides enrichment, some samples fall above LMWL. The GWL for the Central Kabul sub-basin ($\delta^2H = 6.64 \times \delta^{18}O + 4.37$, $R^2 = 0.65$) has a lower slope and intercept than the LWML, indicating evaporation in groundwater samples during the recharge processes and/or mixing with evaporated groundwater.

In arid or semi-arid regions, groundwater influenced by evaporation becomes enriched in heavy isotopes compared to local precipitation, shifting the groundwater line below the LMWL with a lower slope and intercept (Xiang et al., 2021). However, precipitation is the primary contributing source to groundwater in the Central Kabul basin due to the lack of direct infiltration of river water.

The isotopic composition of groundwater samples from the Logar sub-basin have elevated both in $\delta^{18}O$ and δ^2H between 2007 and 2020 while all the samples fall below the LMWL (Fig. 6b). The slope and intercept of GWL for the Logar sub-basin ($\delta^2H = 6.15 \times \delta^{18}O - 2.01$, $R^2 = 0.86$) was below the LMWL. This indicates the groundwater samples were more evaporative in the Logar sub-basin, possibly due to evaporation before recharge, mixing during recharge, and/or irrigation return flow. The isotopic composition of water that has evaporated or been mixed with evaporated water typically shows a lower slope than the GMWL, or LMWL (Clark and Fritz, 1997).

The GWL for Paghman, Lower Kabul and Upper Kabul sub-basins are presented in Fig. 6c, and the GWL ($\delta^2H = 7.04 \times \delta^{18}O + 7.16$, $R^2 = 0.88$) is closest to the LMWL compared to other sub-basins. The isotopic composition of the groundwater samples from the Paghman, Lower Kabul and Upper Kabul sub-basins showed less influence due to evaporation, or had more rainfall input. Due to altitude difference, and low TDS cold groundwater near mountains, the $\delta^{18}O$ values of well water are frequently lower than those of AWAP (Kebede et al., 2005).

4.3. Interaction between surface water and groundwater

The interaction between groundwater and surface water was investigated using the isotopic composition of river water, precipitation and groundwater for 2007 and 2020. Cross-plots of d-excess vs. $\delta^{18}O$ values for the groundwater and river water samples for 2007 and 2020 are shown in Fig. 7a and 7b, respectively. The rain recharge and active recharge were characterized by average $\delta^{18}O$ and d-excess values of precipitation (AWAP) and river water, and the mixed recharge represents an intermediate state between these two mechanisms (Fig. 7a and 7b). Kabul periodically experiences droughts, and the residence time of groundwater is reported to be 15, and 20 years in the study area, based on a few samples (Mack et al., 2010). In this semi-arid region, the observation of Mack et al. (2010) that none of the analysed groundwater samples showed substantial evaporation is unusual. Groundwater samples in 2007 exhibited active recharge conditions since the values closely resembled that of river water, particularly in Paghman and Lower Kabul sub-basins (Fig. 7a). Overall, 11 groundwater samples

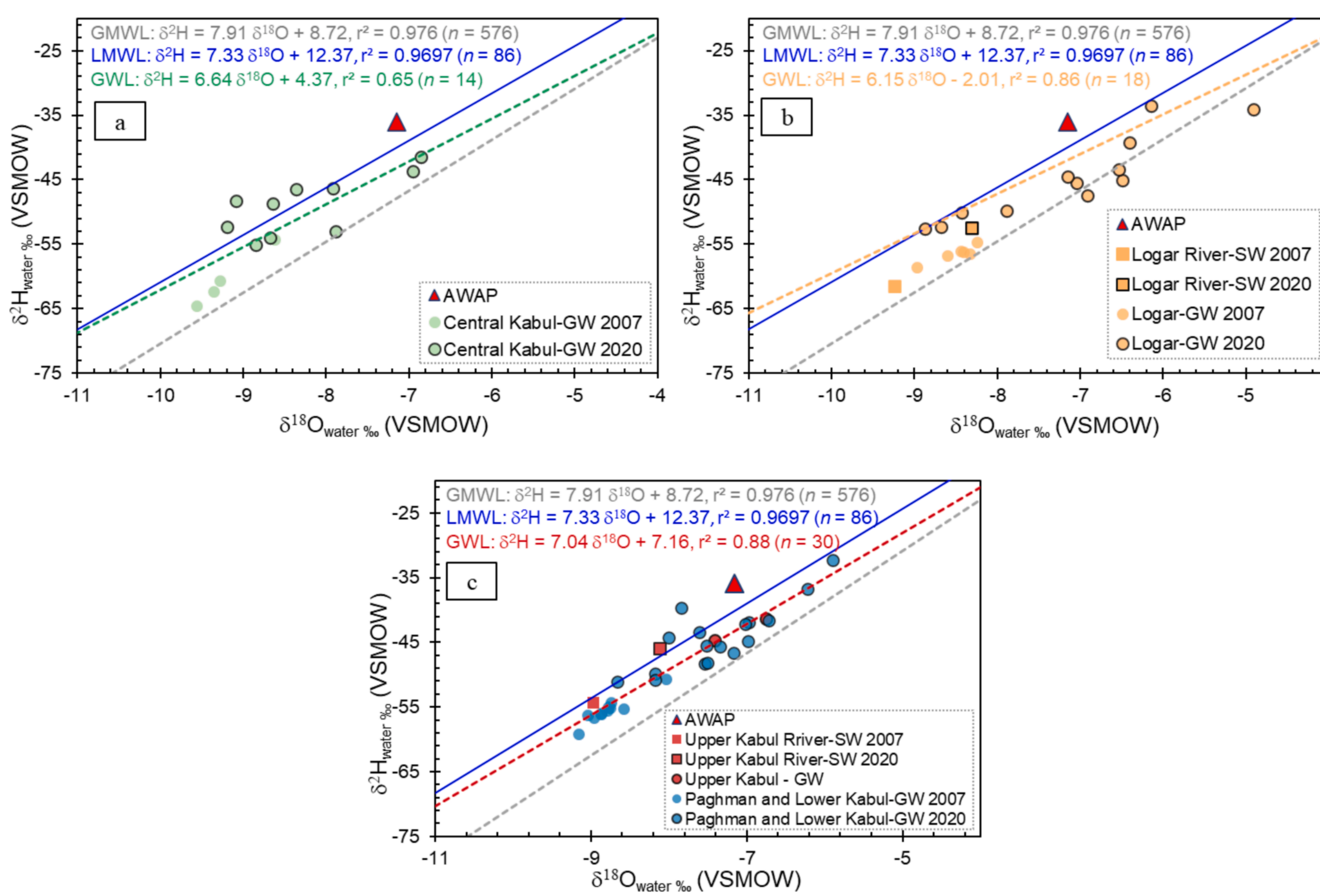

Fig. 6. Cross plots of groundwater δ^2H and $\delta^{18}O$ for Central Kabul (a), Logar (b), and the Upper Kabul and Paghman/Lower Kabul (c).

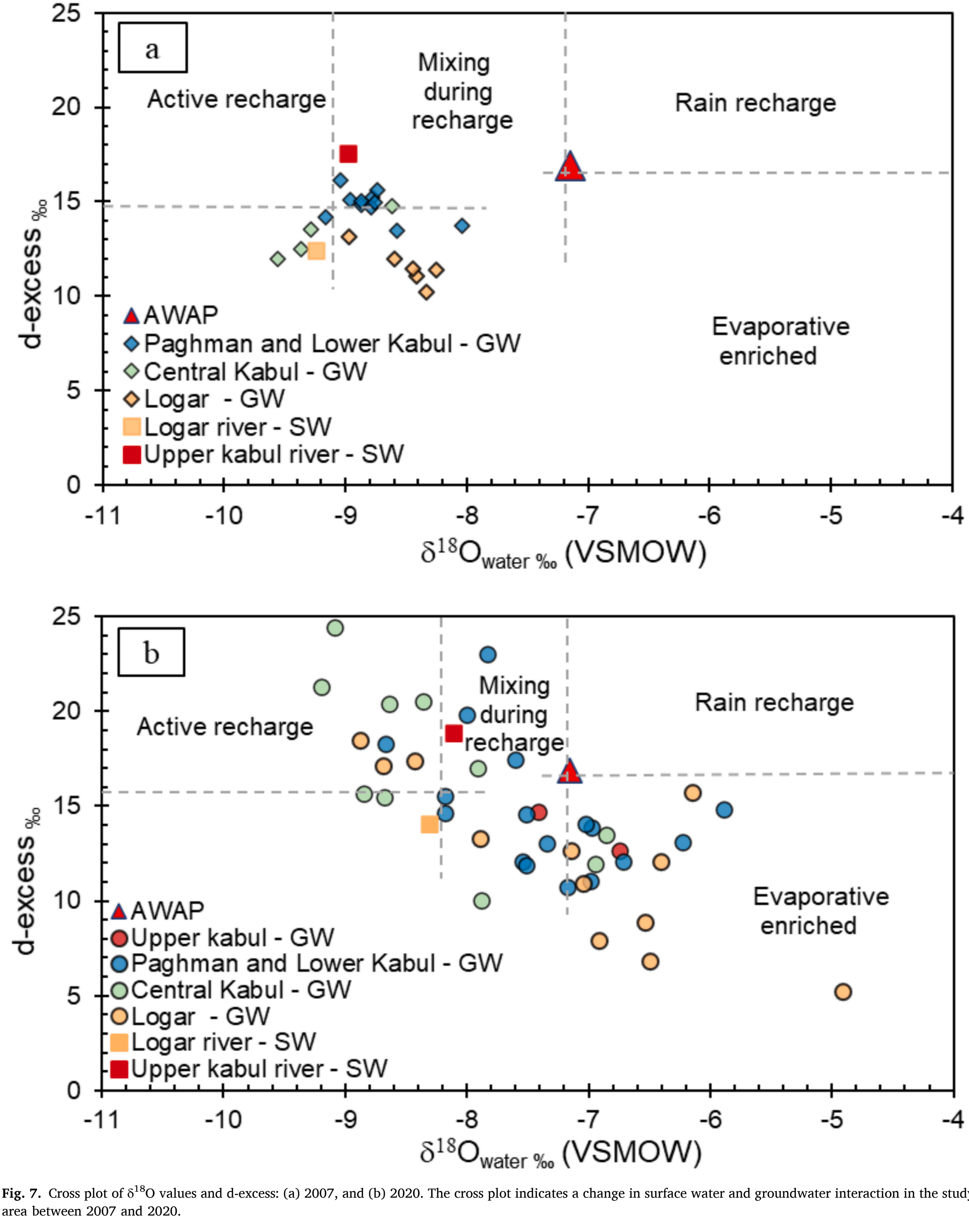

Fig. 7. Cross plot of $\delta^{18}O$ values and d-excess: (a) 2007, and (b) 2020. The cross plot indicates a change in surface water and groundwater interaction in the study area between 2007 and 2020.

show mixed recharge conditions (values fall between river water and precipitation). In general, the groundwater and surface water samples during 2007 featured depleted isotopic composition compared to the AWAP value ($\delta^{18}O$ = -7.2 ‰ and d-excess = +16.9 ‰), which indicates the primary recharge source was from a higher altitude region, depleted isotopic composition in Punjab groundwater is attributed to originating from higher altitudes (Keesari et al., 2017). In contrast, a few groundwater samples in Logar sub-basin had lower d-excess than the river, which is likely due to mixing from various sources and/or irrigation return. Logar River water is extensively diverted for irrigation purposes mainly through ditches, while groundwater is pumped for irrigation during the summer when the river flow is minimal. It is highly plausible that this process affects the isotopic composition of both surface and groundwater. However, it is important to note that our study did not include samples from the canal to directly compare the isotopic compositions before and after the irrigation practices.

Fig. 7b illustrates the groundwater and surface water samples in 2020. The groundwater samples in 2020 had observed enrichment, indicating a change in recharge mechanism between 2007 and 2020. The groundwater recharge in 2020 was dominated by mixing during recharge and evaporative enriched samples. This indicates local factors such as evaporation before and during recharge processes, mixing with surface water or other groundwater, and/or irrigation return, play an important role in modifying the isotopic composition of groundwater in the study area.

Fig. 7 illustrates that the relation between the d-excess and $\delta^{18}O$ was negative in the study area. The majority of water samples in the study area had a value of d-excess of more than 10 ‰, both in 2007 and 2020. The high d-excess values (>10 ‰) in groundwater and surface water samples of the Himalayan region were associated with moisture sources brought by western disturbance (Beg et al., 2022; Jeelani et al., 2021). We utilized NOAA's HYSPLIT atmospheric transport and dispersion modelling system (Stein et al., 2015), to investigate the air mass trajectory. Fig. S4 highlighted that the majority of the winter air mass, in Kabul city, constituting the maximum precipitation period is governed by westerly winds.

4.4. Spatial variation in isotopic characteristics of groundwater

The abundance of $\delta^{18}O$, d-excess is spatially varied in the study area (Fig. 8), ordinary linear kriging was employed to generate interpolation maps - following Frei et al. (2020) and Scheihing et al. (2017). The

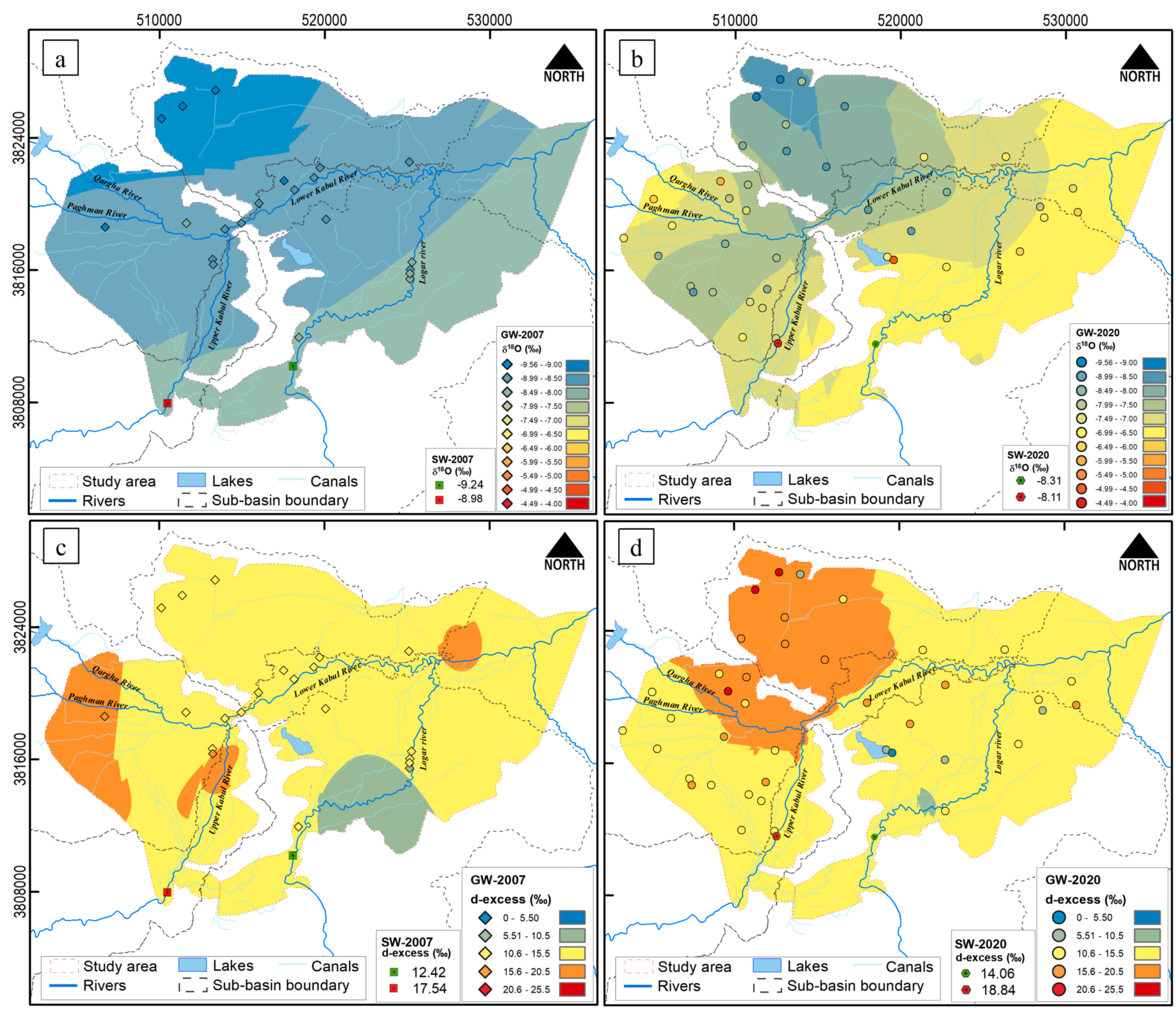

Fig. 8. Spatial distribution of $\delta^{18}O$ in groundwater in 2007 (a) and 2020 (b); d-excess values in groundwater in 2007 (c) and 2020 (d).

Central Kabul sub-basin has not observed significant changes in the depleted $\delta^{18}O$ samples between 2007 (Fig. 8a) and 2020 (Fig. 8b). However, the d-excess values highlight an increasing trend and a few samples have observed 10 ‰ increases between 2007 (Fig. 8c) and 2020 (Fig. 8d). The samples of groundwater that have a depleted isotopic signature may be due to recharge from precipitation.

In Paghman, and the Upper-Kabul and Lower Kabul sub-basins, the changes of $\delta^{18}O$ in groundwater samples located near the rivers followed the river path; in this mainly alluvial system, elevated $\delta^{18}O$ can be observed as the river flows downstream, which also indicates the greater influence of river water recharge in the aquifer. However, the samples located in other parts of the aforementioned sub-basins show a mix of increased or decreased $\delta^{18}O$ values, potentially related to depth, and indicating a higher contribution of precipitation and/or canal water in groundwater recharge (see Fig. S5 for the plot of the relationship between groundwater depth and $\delta^{18}O$). It is important to highlight that most of the groundwater isotopic values in all sub-basins exhibit enrichment between 2007 and 2020 irrespective of depth differences (see Fig. S5). We note elevated $\delta^{18}O$ values of groundwater samples close to the Qargha reservoir ($\delta^{18}O$: −5.9 ‰ and −6.2 ‰), potentially indicating evaporative enrichment (Fig. 8b).

Similarly, in the Logar sub-basin, the $\delta^{18}O$ for groundwater samples located near the rivers, significantly elevated as moving downstream, suggesting that local factors, such as irrigation return, play an important role in modifying the isotopic characteristic of groundwater - water in canals/ditches evaporates and infiltrates en route to irrigated lands. The spatial map (Fig. 8b) highlights a significantly elevated groundwater sample near Heshmat Khan Lake ($\delta^{18}O$: −4.9 ‰), a clear indicator of evaporative enrichment. Spatial differences in groundwater isotope compositions may be caused by the mixing of groundwater of various origins and histories (Sharp, 2017).

Figrr. 8a-b and Fig. 8c-d illustrated that no significant pattern was observed in the isotopic composition of groundwater samples in 2007 and 2020, likely due to the intermixing during the recharge processes.

4.5. Sources of groundwater recharge

Aquifer systems, surface topography, lithology, soil characteristics, and subsurface geometry are primarily responsible for interactions between surface water and groundwater in any given basin. In the present study, we used a two-component mixing model to evaluate mixing during the recharge processes and measure the fraction contributions of surface water and precipitation in the groundwater samples using $\delta^{18}O$ values. One of the main conditions for employing the two-component

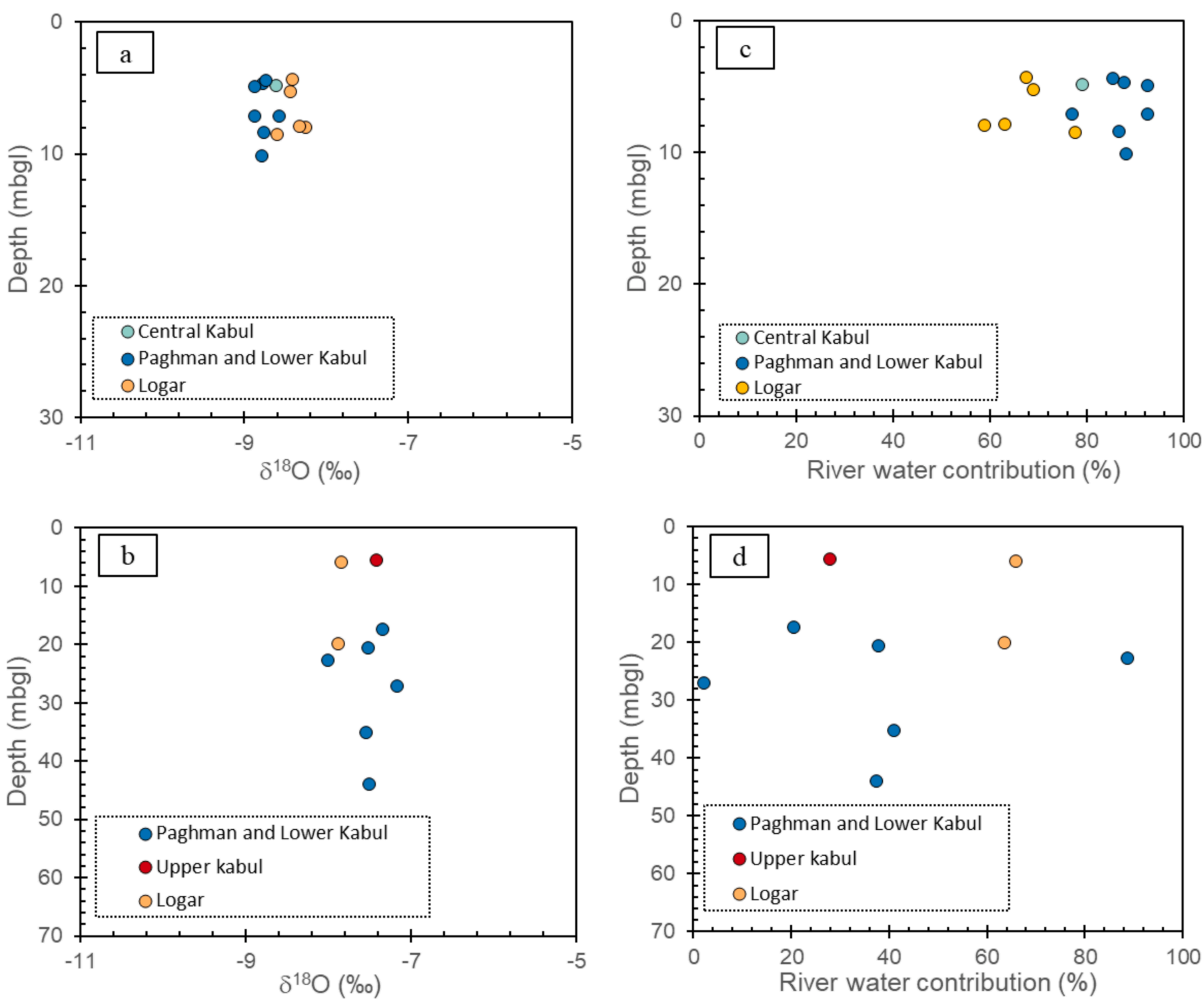

Fig. 9. Depth-wise variation of water to $\delta^{18}O$ values in 2007 (a), and 2020 (b); Depth-wise river water contribution to groundwater in 2007 (a), and 2020 (b).

mixing model is that the values of $\delta^{18}O$ for groundwater samples should fall between rainfall and surface water values of $\delta^{18}O$ (samples falling out of this range were excluded). The river water samples from upstream of two major rivers (Upper Kabul and Logar) constituted one end-member. And, precipitation AWAP was the other end-member component.

Among the samples included in the two-component mixing model, Fig. 9a and 9b indicated that the isotopic composition of groundwater was depleted in 2007 and enriched in 2020 (see Fig. S3 for all samples). In general, any systematic trend in the isotopic composition of groundwater between 2007 and 2020 strongly implies that the groundwater recharge took place under different conditions. This may be consistent with the spatial rise in groundwater storage change rates (see Fig. 3), enriched groundwater infiltration resulted in an increased concentration of $\delta^{18}O$ in groundwater.

The present study also noted site-specific variations in the isotopic composition of groundwater due to depth or increasing distance from upstream of the basin and river. Similarly, utilizing remotely sensed data, Tani and Tayfur (2021) and Mahdawi et al. (2022) suggested that the recharge condition was high in Kabul City. The present study unequivocally demonstrated that active recharging was occurring in Kabul City, however, the recharge process was local, and mixing patterns have been observed.

Fig. 9c and 9d highlighted the contribution of river recharge to groundwater relative to depth. The fraction contribution (%) and $\delta^{18}O$ were spatially different between 2007 and 2020 in all sub-basin. During 2007, the groundwater samples showed higher recharge contribution from the river, and the Upper Kabul, Paghman and Lower Kabul sub-basins received maximum recharge from the river water (fraction contribution: 85 ± 5 % to 92 ± 5 %, $n = 7$). In contrast, the groundwater samples from Upper Kabul, Paghman and Lower Kabul sub-basins revealed less contribution from the river in 2020 (2 ± 5 % to 40 ± 5 %, $n = 7$), which may be related to a shift in recharge pattern; as a result, the groundwater level in the study area showed depletion (see Fig. 2c). Similarly, in the Logar sub-basin, the groundwater samples showed slightly higher recharge contribution from the river in 2007 (59 ± 5 % to 76 ± 5 %, $n = 5$) compared to 2020 (64 ± 5 %, $n = 2$). It is important to note that the average values for both years (in Logar sub-basin) are almost within the range of uncertainties, indicating a relatively consistent trend.

Fig. 10 was generated to explore further the spatial variability of river water conditions. Several groundwater samples ($n = 18$) located near rivers exhibited recharge sources from the river water. The groundwater samples in this alluvial aquifer generally indicated active recharge from various sources, including rivers and precipitation. The groundwater samples near the river showed a higher recharge rate in 2007. Only one sample in 2020 illustrates above 80 % contribution of the river to groundwater; the sample is located in the compound of the National Water Affairs Regulation Authority (NWARA) near a rainwater harvesting pilot project which could have increased the bias toward higher contribution from river water.

The Logar River has a higher inflow into Kabul city compared to the inflow of other sub-basins. Besides the direct water transfer through the canals, the extensive irrigation activities in the Logar sub-basin shape the environment for a river water contribution (over 50 %) in groundwater recharge. However, in the Upper Kabul sub-basin, the contribution of the river to groundwater was spatially different, with an average of below 50 %.

4.6. The conceptual model for representing the geohydrological process

As presented in previous sections, the geohydrological processes

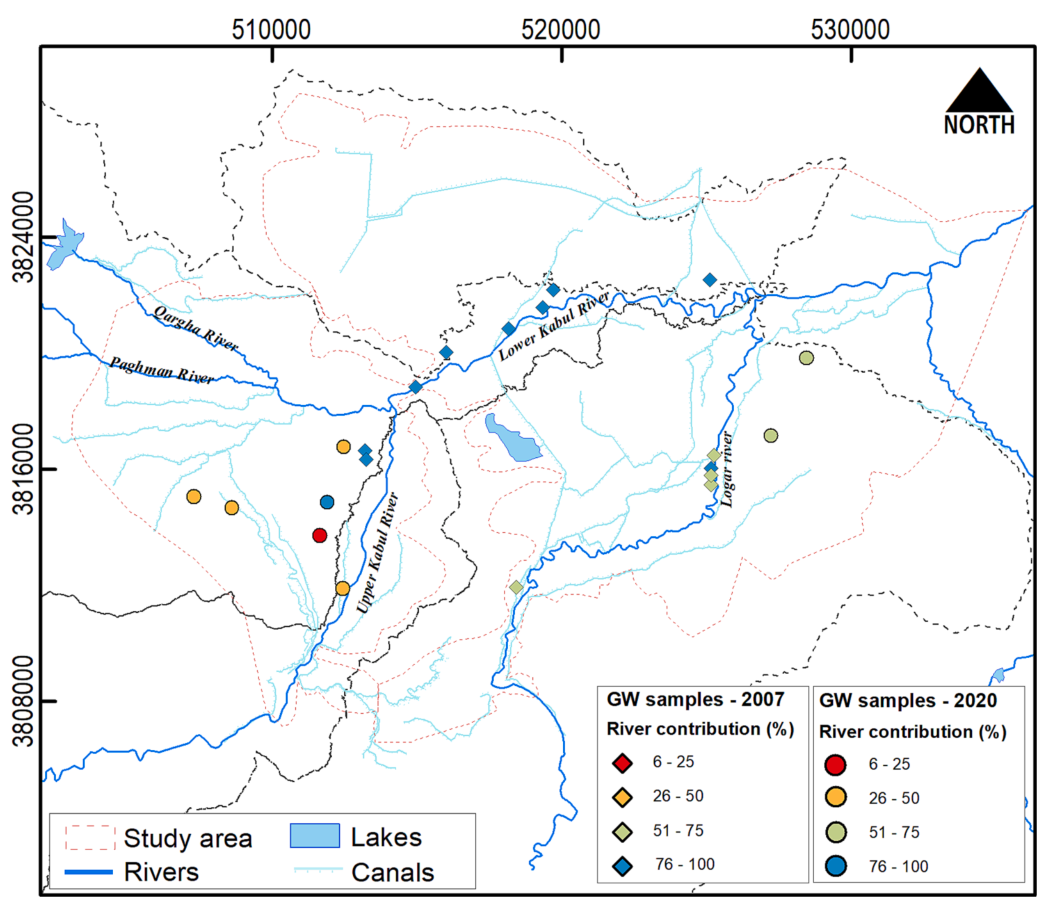

Fig. 10. The spatial variation of the river water contribution to groundwater recharge.

taking place in the sub-basins located in the Kabul city region are varied. The spatial variability in the depth of water level and recharge rate appears to be influenced by complex sub-surface sedimentary architecture. Fig. 11 illustrates a conceptual model representing the geo-hydrological process governing the sub-basin located in Kabul City. The conceptual model was built on the water table data, spatial variability of δ^2H, $\delta^{18}O$ and d-excess values, and river water contribution to groundwater recharge. The complex sub-surface sedimentary structure is thought to impact the spatial variation of depth to water level and recharge rate (see Fig. S1 and S5).

With the use of this conceptual model, our understanding of the lateral and vertical fluctuations of δ^2H, $\delta^{18}O$ and d-excess values in groundwater enhanced, which we ascribe to the uneven distribution of aquifer-and non-aquifer-related sediments in the subsurface. Furthermore, as illustrated in the conceptual model depicted in Fig. 11, the basins located in the study area were distinct in several ways, including the depth of water, geology, and surface water flow. Furthermore, three wellfields are shown around Kabul city which are used for drinking water supply. Meanwhile, the Logar River plays a significant role in contributing to the groundwater recharge of the Logar basin, and the use of groundwater for irrigation which plays a critical role in shaping the isotopic characteristics of groundwater. However, in the Central Kabul sub-basin, the groundwater levels were very low and the only source of recharge appears to be precipitation.

5. Conclusions

This study revealed that the changes in groundwater levels in Kabul City are spatially different. The Central Kabul sub-basin experienced substantial groundwater depletion between 2007 and 2020 (between 35 and 55 m). The western parts of Kabul city (Paghman and Upper-Kabul sub-basins) have also experienced groundwater depletion, where the range of depletion is between 15 and 35 m. However, in the Logar sub-basin and parts of the Lower Kabul sub-basin, there has not been a significant depletion in the groundwater level between 2007 and 2020, and the range has remained almost stable. Groundwater level fluctuations can be connected both spatially and temporally with the geological heterogeneity of the aquifer system, which in turn depends on the composition of the alluvial stratigraphy that lies beneath the study area.

Our findings suggest that the main sources of groundwater recharge in the Kabul city region are local precipitation, river water, and irrigation return flow. These recharge sources vary spatially, the main source of groundwater recharge appeared to be precipitation in Central Kabul sub-basin. The influence of river water to recharge is most apparent in the Logar and Lower Kabul sub-basin. However, the spatial variability in δ^2H and $\delta^{18}O$ values in the western parts of Kabul city (Paghman and Upper-Kabul sub-basins) reflects limited lateral connectivity of the aquifer due to the heterogeneity of aquifer material, whereas the variability of $\delta^{18}O$ with depth demonstrates the impact of averaging the isotopic composition of diverse groundwater sources at different depths. The spatial variability of the stable isotopic data is controlled by local recharge and mixing between surface water and groundwater. The river water contribution to groundwater recharge was, on average over 60 % in 2007 while the contribution has changed on average to less than 50 % in 2020, with notable variations related to depth and spatially. The finding of this study suggests that river water serves as an important source of groundwater recharge in the Kabul city region.

To link the findings of this study with the sustainable groundwater management scenarios, the findings provided important insights for projects such as the Kabul Managed Aquifer Recharge pilot project (KMAR) and follow-up schemes. KMAR uses the substantial water supplies available during the snowmelt and rainy seasons when flows are 15 times higher than in the dry season. Its primary objective is to stabilize or increase groundwater level by artificially enhancing recharge,

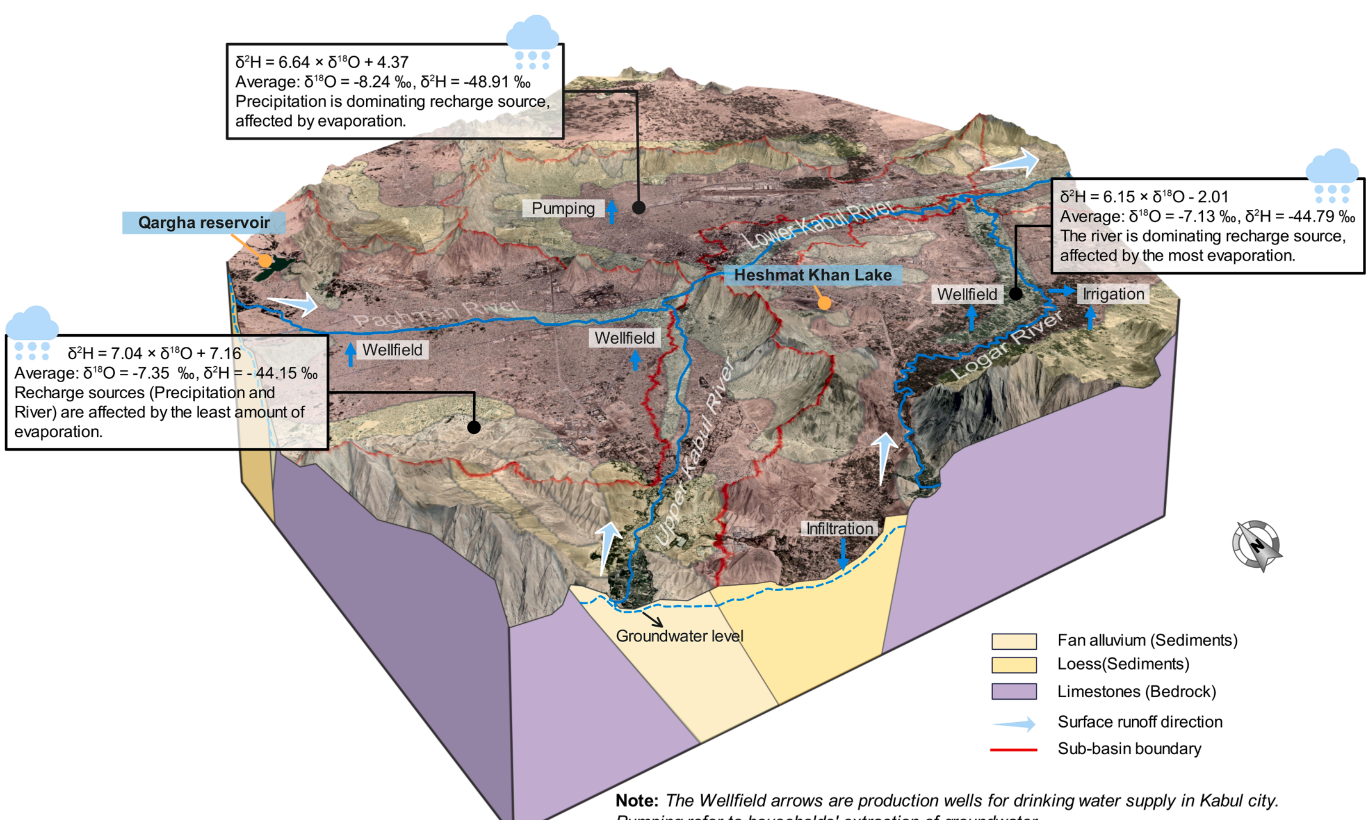

Fig. 11. The conceptual model for groundwater sources in Kabul city, indicating the groundwater (GW) line, $\delta^{18}O$ and δ^2H, and source of groundwater recharge. Data source: Geology from Bohannon and Turner (2007), and Lindsay et al. (2005). Imagery and topography from Google Earth, 2022.

thereby improving water availability for domestic use in Kabul. Additionally, KMAR holds the potential to facilitate the establishment of commercial well-fields (ADB, 2021). Furthermore, the findings of this study provided valuable inputs on understanding water level, surface and groundwater interaction, and groundwater source, which are crucial in designing and implementing strategic plans for the region, namely the Kabul Urban Framework Plan and Sanitation Concept Study project.

Declaration of Competing Interest

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

Data availability

The data is provided as supplementary material.

Acknowledgements

We would like to thank Stephen Kissane, Team leader of the Kabul Managed Aquifer Recharge Project, for his efforts in facilitating the groundwater sampling campaign. We acknowledge the support of Landill-Mills, NWARA, for providing funds for transferring water samples from Kabul to the United Kingdom for analysis. Stable isotope analysis of water samples was internally funded through the Stable Isotope Biogeochemistry Laboratory (SIBL) by DRG. MDH was funded by the Global Challenges Research Fund at Durham University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.130187.

References

ADB, 2021. Kabul Managed Aquifer Recharge Project (49187-002) | Asian Development Bank [WWW Document]. URL https://www.adb.org/projects/49187-002/main (accessed 5.25.23).

Akhtar, F., Awan, U.K., Borgemeister, C., Tischbein, B., 2021. Coupling Remote Sensing and Hydrological Model for Evaluating the Impacts of Climate Change on Streamflow in Data-Scarce Environment. Sustainability 13, 14025. https://doi.org/10.3390/su132414025.

Alley, W.M., Healy, R.W., LaBaugh, J.W., Reilly, T.E., 2002. Flow and storage in groundwater systems. Science 296, 1985–1990. https://doi.org/10.1126/SCIENCE.1067123.

Baig, M.H.A., Abid, M., Khan, M.R., Jiao, W., Amin, M., Adnan, S., 2020. Assessing Meteorological and Agricultural Drought in Chitral Kabul River Basin Using Multiple Drought Indices. Remote Sensing 12, 1417. https://doi.org/10.3390/rs12091417.

Beg, Z., Joshi, S.K., Singh, D., Kumar, S., Gaurav, K., 2022. Surface water and groundwater interaction in the Kosi River alluvial fan of the Himalayan foreland. Environmental Monitoring and Assessment 194, 556. https://doi.org/10.1007/s10661-022-10192-8.

Bhanja, S.N., Mukherjee, A., Rangarajan, R., Scanlon, B.R., Malakar, P., Verma, S., 2019. Long-term groundwater recharge rates across India by in situ measurements. Hydrology and Earth System Sciences 23, 711–722. https://doi.org/10.5194/HESS-23-711-2019.

Bohannon, R., Turner, K., 2007. Geologic map of quadrangle 3468, chak Wardak-Syahgerd (509) and kabul (510) quadrangle, Afghanistan. U. S. Geological Survey.

Bohannon, R.G., 2010. Geologic and topographic maps of the kabul south 30’ × 60’ quadrangle, Afghanistan. U. S. Geological Survey.

Bowen, G.J., Putman, A., Brooks, J.R., Bowling, D.R., Oerter, E.J., Good, S.P., 2018. Inferring the source of evaporated waters using stable H and O isotopes. Oecologia 187, 1025–1039. https://doi.org/10.1007/s00442-018-4192-5.

Brati, M.Q., Ishihara, M.I., Higashi, O., 2019. Groundwater level reduction and pollution in relation to household water management in Kabul, Afghanistan. Sustain Water Resour Manag 5, 1315–1325. https://doi.org/10.1007/s40899-019-00312-7.

Broshears, R.E., Akbari, M.A., Chornack, M.P., Mueller, D.K., Ruddy, B.C., 2005. Inventory of ground-water resources in the Kabul Basin, Afghanistan. U. S. Geological Survey.

Böckh, E.G., 1971. Report on the groundwater resources of the City of Kabul.

Clark, I.D., Fritz, P., 1997. Environmental isotopes in hydrogeology. CRC Press.

Clark, I., 2015. Groundwater Geochemistry and Isotopes, 1st ed. CRC Press, Boca Raton. https://doi.org/10.1201/b18347.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 436–468. https://doi.org/10.1111/J.2153-3490.1964.TB00181.X.

Davisson, M.L., Smith, D.K., Kenneally, J., Rose, T.P., 1999. Isotope hydrology of southern Nevada groundwater: Stable isotopes and radiocarbon. Water Resources Research 35, 279–294. https://doi.org/10.1029/1998WR900040.

Google Earth, 2022. Google Earth.

Esri, 2019. ArcGIS Desktop 10.7.1 quick start guide—ArcMap.Esri.

Favre, A., Kamal, G.M., 2004. Watershed atlas of Afghanistan.

Frei, R., Frei, K.M., Kristiansen, S.M., Jessen, S., Schullehner, J., Hansen, B., 2020. The link between surface water and groundwater-based drinking water – strontium isotope spatial distribution patterns and their relationships to Danish sediments. Applied Geochemistry 121, 104698. https://doi.org/10.1016/J.APGEOCHEM.2020.104698.

Gat, J.R., 1983. Precipitation, Groundwater and Surface waters. Control of climate parameters on their isotopic composition and their utilization as palaeoclimatological tools, in: Proceedings of an advisory group meeting on the variations of the Isotopic Composition of precipitation and of Groundwater during the quaternary as a consequence of climatic changes. International Atomic Energy Agency, Vienna, pp. 3–12.

Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. Annual Review of Earth and Planetary Sciences 24, 225–262.

Genereux, D., 1998. Quantifying uncertainty in tracer-based hydrograph separations. Water Resources Research 34, 915–919. https://doi.org/10.1029/98WR00010.

Ghulami, M., Gourbesville, P., Audra, P., Shie-Yui, L., 2022. Performance evaluation of CORDEX south Asia models for projections of precipitation over the Kabul Basin, Afghanistan. Hydroscience Journal 108. https://doi.org/10.1080/27678490.2022.2095936.

Giggenbach, W.F., 1992. Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin. Earth and Planetary Science Letters 113, 495–510. https://doi.org/10.1016/0012-821X(92)90127-H.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E., Cardenas, M.B., 2015. The global volume and distribution of modern groundwater. Nature Geoscience 9, 161–167. https://doi.org/10.1038/ngeo2590.

Hamidi, M.D., Kissane, S., Bogush, A.A., Qayeum, A.K., Sagintayev, J., Towers, S., Greenwell, H.C., 2023. Spatial estimation of groundwater quality, hydrogeochemical investigation, and health impacts of shallow groundwater in Kabul city, Afghanistan. Sustain Water Resour Manag 9, 1–14. https://doi.org/10.1007/S40899-022-00808-9.

Healy, R.W., Cook, P.G., 2002. Using groundwater levels to estimate recharge. Hydrogeology Journal 10, 91–109. https://doi.org/10.1007/s10040-001-0178-0.

Herrmann, A., Stichler, W., 1980. Groundwater-Runoff relationships. Catena 7, 251–263. https://doi.org/10.1016/S0341-8162(80)80017-8.

Hossaini, M.S., 2019. پهنه بندی ژیوتکنیکی ناحیه شهری کابل از نظر نوع خاک [Geotechnical zonation of Kabul urban area according to soil type]. Engineering Sina 1, 1–9.

Hughes, C.E., Crawford, J., 2012. A new precipitation weighted method for determining the meteoric water line for hydrological applications demonstrated using Australian and global GNIP data. Journal of Hydrology 464–465, 344–351. https://doi.org/10.1016/J.JHYDROL.2012.07.029.

Hussaini, M.S., Farahmand, A., Shrestha, S., Neupane, S., Abrunhosa, M., 2022. Site selection for managed aquifer recharge in the city of Kabul, Afghanistan, using a multi-criteria decision analysis and geographic information system. Hydrogeology Journal 30, 59–78. https://doi.org/10.1007/s10040-021-02408-x.

IAEA/WMO, 2022. Global Network of Isotopes in Precipitation [WWW Document]. The GNIP Database. URL https://nucleus.iaea.org/wiser/ (accessed 7.18.22).

Jasechko, S., Perrone, D., Befus, K.M., Bayani Cardenas, M., Ferguson, G., Gleeson, T., Luijendijk, E., McDonnell, J.J., Taylor, R.G., Wada, Y., Kirchner, J.W., 2017. Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. Nature Geoscience 10, 425–429. https://doi.org/10.1038/ngeo2943.

Jasechko, S., 2019. Global isotope Hydrogeology-Review. Reviews of Geophysics 57, 835–965. https://doi.org/10.1029/2018RG000627.

Jawadi, H.A., Sagin, J., Snow, D.D., 2020. A detailed assessment of groundwater quality in the Kabul Basin, Afghanistan, and suitability for future development. Water 12, 2890. https://doi.org/10.3390/w12102890.

Jeelani, G., Saravana Kumar, U., Kumar, B., 2013. Variation of $\delta^{18}O$ and δD in precipitation and stream waters across the Kashmir Himalaya (India) to distinguish and estimate the seasonal sources of stream flow. J Hydrol 481, 157–165. https://doi.org/10.1016/J.JHYDROL.2012.12.035.

Jeelani, G., Lone, S.A., Nisa, A.U., Deshpande, R.D., Padhya, V., 2021. Use of stable water isotopes to identify and estimate the sources of groundwater recharge in an alluvial aquifer of Upper Jhelum Basin (UJB), western Himalayas. Hydrological Sciences Journal 66, 2330–2339. https://doi.org/10.1080/02626667.2021.1985126.

JICA, 2011. The Study on Groundwater Resources Potential in Kabul Basin in The Islamic Republic of Afghanistan. Kabul, Afghanistan. GED.JR.11-077.

Joshi, S.K., Rai, S.P., Sinha, R., Gupta, S., Densmore, A.L., Rawat, Y.S., Shekhar, S., 2018. Tracing groundwater recharge sources in the northwestern Indian alluvial aquifer using water isotopes ($\delta^{18}O$, $\delta^{2}H$ and 3H). J Hydrol 559, 835–847. https://doi.org/10.1016/j.jhydrol.2018.02.056.

Kebede, S., Travi, Y., Alemayehu, T., Ayenew, T., 2005. Groundwater recharge, circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Applied Geochemistry 20, 1658–1676. https://doi.org/10.1016/J.APGEOCHEM.2005.04.016.

Keesari, T., Sharma, D.A., Rishi, M.S., Pant, D., Mohokar, H.V., Jaryal, A.K., Sinha, U.K., 2017. Isotope investigation on groundwater recharge and dynamics in shallow and

deep alluvial aquifers of southwest Punjab. Applied Radiation and Isotopes 129, 163–170. https://doi.org/10.1016/j.apradiso.2017.07.022.
Kloppmann, W., Girard, J.-P., Négrel, P., 2002. Exotic stable isotope compositions of saline waters and brines from the crystalline basement. Chemical Geology 184, 49–70. https://doi.org/10.1016/S0009-2541(01)00352-7.
Kumar, B., Rai, S.P., Kumar, U.S., Verma, S.K., Garg, P., Kumar, S.V.V., Jaiswal, R., Purendra, B.K., Kumar, S.R., Pande, N.G., 2010. Isotopic characteristics of Indian precipitation. Water Resources Research 46. https://doi.org/10.1029/2009WR008532.
Kumar, S., Joshi, S.K., Pant, N., Singh, S., Chakravorty, B., Saini, R.K., Kumar, V., Singh, A., Ghosh, N.C., Mukherjee, A., Rai, P., Singh, V., 2021. Hydrogeochemical evolution and groundwater recharge processes in arsenic enriched area in central gangetic plain, India. Applied Geochemistry 131. https://doi.org/10.1016/j.apgeochem.2021.105044.
Li, Y., Bian, J., Li, J., Ma, Y., Anguiano, J.H.H., 2022. Hydrochemistry and stable isotope indication of natural mineral water in Changbai Mountain China. J Hydrol Reg Stud 40, 101047. https://doi.org/10.1016/J.EJRH.2022.101047.
Lindsay, C., Snee, L., Bohannon, R., Wahl, R., Sawyer, D., 2005. Geologic map of quadrangle 3568, polekhomri (503) andCharikar (504) quadrangles, Afghanistan. U. S. Geological Survey.
Mack, T.J., Akbari, M.A., Ashoor, M.H., Chornack, M.P., Coplen, T.B., Emerson, D.G., Hubbard, B.E., Litke, D.W., Michel, R.L., Plummer, N., Rezai, M.T., Senay, G.B., Verdin, J.P., Verstraeten, I.M., J. Mack, T., Akbari, M.A., Ashoor, M.H., Chornack, M. P., Coplen, T.B., Emerson, D.G., Hubbard, B.E., Litke, D.W., Michel, R.L., Plummer, L.N., Rezai, M.T., B. Sena, G., P. Verdin, J., M. Verstraeten, I., 2010. Conceptual model of water resources in the Kabul Basin, Afghanistan, Scientific Investigations Report. Reston, Virginia.
Mack, T.J., Chornack, M.P., Taher, M.R., 2013. Groundwater-level trends and implications for sustainable water use in the kabul basin, afghanistan. Environ Syst Decis 33, 457–467. https://doi.org/10.1007/s10669-013-9455-4.
Maharjan, S.B., Mool, P.K., Lizong, W., Xiao, G., Shrestha, F., Shrestha, R.B., Khanal, N. R., Bajracharya, S.R., Shai, S., Baral, P., 2018. The Status of Glacial Lakes in the Hindu Kush Himalaya - ICIMOD. Research Report 2018/1. https://doi.org/10.53055/ICIMOD.742.
Mahdawi, Q., Sagin, J., Absametov, M., Zaryab, A., 2022. Water recharges suitability in Kabul Aquifer System within the Upper Indus Basin. Water 14, 2390. https://doi.org/10.3390/w14152390.
Masoom, M.F., 2018. Artificial recharge of groundwater as a management tool for the Kabul Basin, Afghanistan (Master's theses). Graduate faculty of the Louisiana. State University and Agricultural and Mechanical College.
Meldebekova, G., Yu, C., Li, Z., Song, C., 2020. Quantifying ground subsidence associated with aquifer overexploitation using Space-Borne radar interferometry in Kabul, Afghanistan. Remote Sens 12, 2461. https://doi.org/10.3390/rs12152461.
Merlivat, L., Jouzel, J., 1979. Global climatic interpretation of the deuterium-oxygen 16 relationship for precipitation. Journal of Geophysical Research 84, 5029–5033. https://doi.org/10.1029/JC084iC08p05029.
Milly, P.C.D., Dunne, K.A., Vecchia, A.v., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347–350. https://doi.org/10.1038/nature04312.
Nasir, M.J., Khan, S., Ayaz, T., Khan, A.Z., Ahmad, W., Lei, M., 2021. An integrated geospatial multi-influencing factor approach to delineate and identify groundwater potential zones in Kabul province. Afghanistan. Environ Earth Sci 80. https://doi.org/10.1007/s12665-021-09742-z.
NISA, 2020. Estimated Population of Afghanistan 2020-21. NISA.
Noori, A.R., Singh, S.K., 2021. Spatial and temporal trend analysis of groundwater levels and regional groundwater drought assessment of Kabul, Afghanistan. Environ Earth Sci 80, 698. https://doi.org/10.1007/s12665-021-10005-0.
Opie, S., Taylor, R.G., Brierley, C.M., Shamsudduha, M., Cuthbert, M.O., 2020. Climate-groundwater dynamics inferred from GRACE and the role of hydraulic memory. Earth System Dynamics 11, 775–791. https://doi.org/10.5194/ESD-11-775-2020.
POWER-Project, 2022. Prediction of worldwide energy resources [WWW document]. URL https://power.larc.nasa.gov/. (accessed 8.25.22).
Rai, S.P., Kumar, B., Singh, P., 2009. Estimation of contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas, India, using oxygen-18 isotope. Current Science 97, 240–245. https://www.jstor.org/stable/24111923.
Rai, S.P., Noble, J., Singh, D., Rawat, Y.S., Kumar, B., 2021. Spatiotemporal variability in stable isotopes of the Ganga River and factors affecting their distributions. Catena 204, 105360. https://doi.org/10.1016/j.catena.2021.105360.
Sadid, N., 2020. Surface-groundwater interaction in the Kabul region basin. Afghanistan Research and Evaluation Unit.
Saffi, M.H., 2011. Groundwater natural resources and quality concern in Kabul basin, Afghansitan. DACAAR.
Saffi, M.H., 2014. National Groundwater Monitoring Wells Network data evaluation Finding, Challenges and Recommended solution. DACAAR.
Saffi, M.H., 2019. National alarming on groundwater natural storage depletion and water quality deterioration of Kabul City and immediate response to the drinking water crises. DACAAR.
Scheihing, K., Moya, C., Struck, U., Lictevout, E., Tröger, U., 2017. Reassessing hydrological processes that control stable isotope tracers in groundwater of the Atacama Desert (Northern Chile). Hydrology 5, 3. https://doi.org/10.3390/hydrology5010003.
Semwal, P., Khobragarde, S., Joshi, S.K., Kumar, S., 2020. Variation in $\delta^{18}O$ and $\delta^{2}H$ values of rainfall, surface water, and groundwater in the Sukhna Lake basin in northwest India. Environment and Earth Science 79. https://doi.org/10.1007/s12665-020-09285-9.
Sharp, Z., 2017. Principles of Stable Isotope Geochemistry, 2nd Editio. ed. University of New, Mexico. https://doi.org/10.25844/h9q1-0p82.
Sheikhi, S., Shahbazi, H., Mosaferi, M., Firuzi, P., Aslani, H., 2020. Spatio-temporal variation of WQI, scaling and corrosion indices, and principal component analysis in rural areas of Marand, Iran. Groundw Sustain Dev 11, 100480. https://doi.org/10.1016/j.gsd.2020.100480.
Singh, S.K., Noori, A.R., 2022. Delineation of groundwater recharge potential zones for its sustainable development utilizing GIS approach in Kabul Basin, Afghanistan. Arabian Journal of Geosciences 15. https://doi.org/10.1007/s12517-021-09410-3.
Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIt Atmospheric Transport and Dispersion modeling system. Bulletin of the American Meteorological Society 96, 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1.
Tani, H., Tayfur, G., 2021. Identification of groundwater potential zones in Kabul River Basin, Afghanistan. Groundw Sustain Dev 15, 13. https://doi.org/10.1016/j.gsd.2021.100666.
Terzer, S., Wassenaar, L.I., Araguás-Araguás, L.J., Aggarwal, P.K., 2013. Global isoscapes for $\delta^{18}O$ and $\delta^{2}H$ in precipitation: Improved prediction using regionalized climatic regression models. Hydrology and Earth System Sciences 17, 4713–4728. https://doi.org/10.5194/HESS-17-4713-2013.
Uhlenbrook, S., Hoeg, S., 2003. Quantifying uncertainties in tracer-based hydrograph separations: A case study for two-, three- and five-component hydrograph separations in a mountainous catchment. Hydrological Processes 17, 431–453. https://doi.org/10.1002/HYP.1134.
Williams, A.E., Rodoni, D.P., 1997. Regional isotope effects and application to hydrologic investigations in southwestern California. Water Resources Research 33, 1721–1729. https://doi.org/10.1029/97WR01035.
Xiang, W., Si, B., Li, M., Li, H., Lu, Y., Zhao, M., Feng, H., 2021. Stable isotopes of deep soil water retain long-term evaporation loss on China's loess plateau. Science of The Total Environment 784, 147153. https://doi.org/10.1016/J.SCITOTENV.2021.147153.
Xie, C., Zhao, L., Eastoe, C.J., Wang, N., Dong, X., 2022. An isotope study of the ShuleRiver Basin, Northwest China: Sources and groundwater residence time, sulfate sources and climate change. J Hydrol 612, 128043. https://doi.org/10.1016/J.JHYDROL.2022.128043.
Zaryab, A., Reza Noori, A., Wegerich, K., Kløve, B., 2017. Assessment of water quality and quantity trends in Kabul aquifers with an outline for future drinking water supplies. Central Asian Journal of Water Research 3, 3–11.
Zaryab, A., Nassery, H.R., Alijani, F., 2022a. The effects of urbanization on the groundwater system of the Kabul shallow aquifers, Afghanistan. Hydrogeol J. https://doi.org/10.1007/S10040-021-02445-6.
Zaryab, A., Nassery, H.R., Knoeller, K., Alijani, F., Minet, E., 2022b. Determining nitrate pollution sources in the Kabul plain aquifer (Afghanistan) using stable isotopes and bayesian stable isotope mixing model. Science of the Total Environment 823. https://doi.org/10.1016/j.scitotenv.2022.153749.
Zhou, J.-L., Li, T.-Y., 2018. A tentative study of the relationship between annual $\delta^{18}O$ & δD variations of precipitation and atmospheric circulations—A case from southwest china. Quaternary International 479, 117–127. https://doi.org/10.1016/j.quaint.2017.05.038.