ORIGINAL ARTICLE

Variation in $\delta^{18}O$ and δ^2H values of rainfall, surface water, and groundwater in the Sukhna Lake basin in northwest India

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Abstract

Sukhna Lake in the Himalayan foothills is a vital wetland with important ecological functions in north India. In the present study, we have collected water samples from rainfall ($n = 482$), surface water ($n = 146$), and groundwater ($n = 404$) during 2011–2017 for isotopic analysis ($\delta^{18}O$ and δ^2H) to understand the recharge processes in the Sukhna Lake basin. The $\delta^{18}O$ and δ^2H values of rainfall show seasonality across the study area due to the different vapor sources. The moisture source for precipitation is the Arabian Sea during the monsoon season (July–September) and from a westerly source during winters (December–January). The $\delta^{18}O$ and δ^2H values of the surface water bodies show an evaporative signature across the study area. We also observed spatial and depth-related variations in the $\delta^{18}O$ and δ^2H values of groundwater. Here, we categorized groundwater samples into two depth zones based on the surface topography, isotopic values of groundwater, and aquifer characteristics. The groundwater zone-1a-b (depth: < 65 m below ground level (bgl)) shows active recharge processes because of rainfall recharge and seepage from surface water bodies. We observed the dominance of precipitation recharge in groundwater zone-2 (depth: > 150 m bgl) due to the regional groundwater flow pattern. We suggest two groundwater flow patterns present in the study area: local flow system is limited to zone-1a-b, whereas the regional flow pattern can be seen in zone-2. The present study provides new insight into the study area's recharge mechanism to understand the hydrological processes in any lake basin.

Introduction

Lakes are a significant component in the hydrological system (Krabbenhoft et al. 1990; Abuduwaili et al. 2019) and have an important socioeconomic role for many communities (Cui and Li 2015; Freitas et al. 2019; Wan et al. 2019). The chemical composition of water in many lakes can vary seasonally due to various contributing factors, such as the effects of rainfall, surface runoff, and baseflow (groundwater) contribution from the lake basin (Krabbenhoft et al. 1990). Evaporation and evapotranspiration play an important

role in controlling the lake water level in any given basin (Labrecque et al. 2009; Turner et al. 2014; Abuduwaili et al. 2019). The hydrological budget can be estimated using the lake water level fluctuation (Muvundja et al. 2014). The lake water fluctuation can also help understand the climatic variability in/around the nearby region (Lenters et al. 2005). Therefore, it is necessary to understand the recharge processes of the lake basin.

Determining the stable isotopic composition ($\delta^{18}O$ and δ^2H) of rainfall, surface water, and groundwater is a useful method for: identifying the source of vapor that produces precipitation in a given region at a specific time of the year (Clark and Fritz 1997; Lone et al. 2019); for determining the interaction between surface water and groundwater (Joshi et al. 2018, 2020); and for determining groundwater dynamics (Maloszewski et al. 1987; Krabbenhoft et al. 1990; Clark and Fritz 1997; Hunt et al. 2005; Joshi et al. 2014).

Numerous researchers have investigated groundwater–surface water interaction using an isotopic approach and identified the origin of different components of

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hydrological cycles (Nachiappan et al. 2002; Yang et al. 2012; Chiogna et al. 2014; Zhan et al. 2016). Ichiyanagi et al. (2003) analyzed seasonality in the isotopic composition of Alas Lake in Eastern Siberia. Tian et al. (2008) studied the isotopic variations in the lake water balance for the Yamdruk-tso basin, southern Tibetan Plateau. Perini et al. (2009) used multi-year $\delta^{18}O$ values for six lakes in the Italian Alps to understand the lakes' hydrological dynamics. Sacks et al. (2014) used an isotope mass balance approach to quantify transient groundwater and lake water interactions. Shaw et al. (2017) assessed groundwater inflow and leakage outflow for Georgetown Lake in Montana, USA, with the use of stable isotopes of $\delta^{18}O$ and δ^2H. A small number of local studies were published on the lake basin in north India to understand the groundwater–surface water interaction using the isotopic approach (Nachiappan et al., 2002; Gupta and Deshpande, 2004). Nachiappan et al. (2002) and Gupta and Deshpande (2004) used a water balance model based on a tracer-based technique and identified surface water and groundwater interaction in Nainital Lake basin in north India.

The present study focuses on the Sukhna Lake basin in north India. Up until now, there has been no systematic study (based on available literature) of the interaction between groundwater and surface water and of the vapor source identification in northwest India's Sukhna Lake basin. Therefore, we used a systematic isotopic study of $\delta^{18}O$ and δ^2H of rainfall, surface water (Sukhna lake, check dams and ponds), and

groundwater to understand the hydrological processes and recharge mechanism.

The specific objectives of the present study are: (i) to identify the isotopic composition of waters (rainfall, surface water, and groundwater) and vapor sources for the Sukhna Lake basin in northwest India; and (ii) to determine the recharge processes of the study area using stable isotope measurements.

Study area description

The present study is focused on the Sukhna Lake basin (Fig. 1), which is located in the Union Territory of Chandigarh in north India. Sukhna Lake is a famous tourist attraction and is a center of recreation in north India. The study area falls between latitude 30°44′6.75″ N and 30°49′7″ N and longitude 76°48′16.79″ E and 76°53′38.26″ E, and is located in the upstream parts of the Ghaggar River basin in north India. It covers an area of ~ 42 km², of which the Sukhna Lake area is about ~ 1.66 km² (Semwal et al. 2013), and the remaining area is in the Himalayan mountains and a piedmont region (van Dijk et al. 2016, 2020; Joshi et al. 2018, 2020; Shekhar et al. 2018, 2020).

Sukhna Lake was constructed in 1958 and is ~ 2.3 km long and ~ 1.06 km wide. The elevation of the lake bed varies between about 357 m above sea level (ASL) (maximum) and 349 m asl (minimum). The maximum depth of the lake is about 8 m and its average depth is about 3 m. The lake
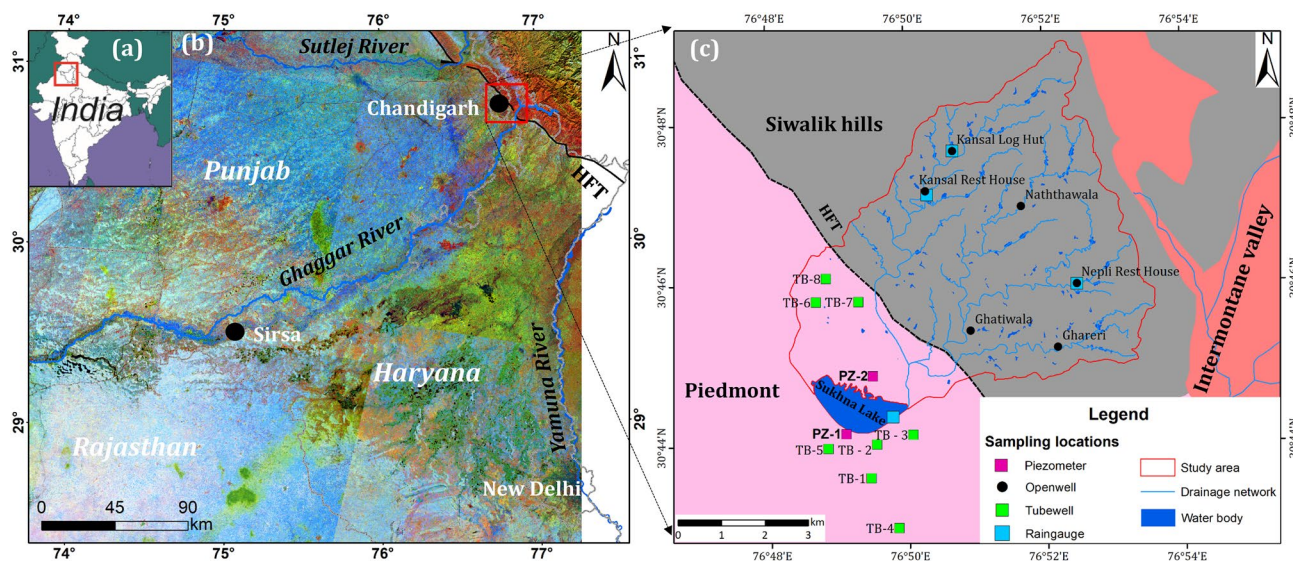

Fig. 1 An overview map of the study area. **a** The political boundary of India. **b** Landsat-5 bands 4, 5 and 6 (RGB). **c** Geomorphic map of the study area, modified after van Dijk et al. (2016) and Joshi et al. (2018). The continuous blue lines represent surface rivers: the Sukhna Lake and other surface water bodies are shown by the blue polygon. Four rain gauges were installed at Sukhna Lake, Nepli Rest

House, Kansal Rest House and Kansal Log Hut (blue squares) to collect precipitation samples. Tube well sampling locations are shown by green squares, open well locations by black circles, and piezometer stations by pink squares. A red color boundary shows the Sukhna Lake basin

has been classified as a wetland of national importance by the Chandigarh Administration and the National Wetland Committee, Ministry of Environment, Government of India (Khobragade et al. 2013; Semwal et al. 2013). The lake serves as a sanctuary for many birds in north India (Singh 2002). In recent years, the volume of water in the lake has been progressively declining, thus creating threats to its existence. This factor, coupled with the degradation of water quality in the lake, has reduced the esthetic and environmental values associated with this wetland, causing threats to tourism and ecology.

The study area has a sub-tropical climate where the temperature ranges from a minimum of about 1 °C during winter to a maximum of about 45 °C during summers (Joshi et al. 2018, 2020). The study area can be characterized in four seasons based on their characteristics. These are the (a) pre-monsoon season (April–June), (b) monsoon season (July–September), (c) post-monsoon season (October to November), and (d) winter season (December–March). Generally, the average annual rainfall is about 1122 mm, with a variation of about 23%. About 80% of the rain falls during the monsoon season and the remaining 20% falls during the non-monsoon season due to the effects of air masses that bring moisture into the study area from a westerly direction (Lone et al. 2019).

Hydrogeological settings of the study area

The present study area coincides with two different hydrogeological units: the Siwalik Hills and the Piedmont area (Fig. 1). The Siwalik Hills (middle Miocene age: CGWB 2007) are made up of sandstones and conglomerates and are separated from the Indo-Gangetic foreland basin by Himalayan Frontal Thrust (HFT). By contrast, the foreland basin consists of sand, silt, and clay deposits (UNDP 1985; Sinha et al. 2013; van Dijk et al. 2016). The Piedmont region is characterized by thinner and less abundant aquifer bodies located close to the HFT. The piedmont deposits comprise boulder, pebble, and cobble associated with the clay, sand and silt. The alluvium region follows the Piedmont deposits in the study area's downstream region and comprises finer sediments such as clay, silt, and sand (CGWB, 2009).

The aquifer system in the study area consists of a shallow (Aquifer-I) and a deep (Aquifer-II) aquifer (CGWB 2009). The Aquifer-I is generally unconfined up to the depth of 80 m bgl (Joshi et al. 2018) and semi-confined up to 150 m bgl. Groundwater in Aquifer-II is subjected to semi-confined to confined conditions, and its depth range is from 150 to 250 m bgl (CGWB 2009; van Dijk et al. 2016). The transmissivity range varies from 70 to 466 m^2/day for the shallow aquifer and from 74 to 590 m^2/day for deeper aquifer in the study area (CGWB 2007). The groundwater flow direction

is from northeast to southwest (Joshi et al. 2014; Shekhar et al. 2020). The water table shows a steep hydraulic gradient in the upper segment and a gentle slope toward the study area's downstream region. The water table varies from 2 to 40 m bgl in the study area (CGWB 2007; Joshi et al. 2014; Sinha et al. 2019).

Materials and methods

Sampling point distribution and water sampling

We have designed a systemic water sampling strategy based on the study area's surface topographic and geomorphic settings. We have collected water samples from rainfall, surface water (lake, check dams and ponds), and groundwater (open wells, piezometers, and tube wells) for isotopic analysis. A total of 482 rainfall samples were collected from the Kansal Rest House ($n = 134$), Kansal Log Hut ($n = 79$), Nepli Rest House ($n = 98$), and Sukhna Lake ($n = 171$) gauge stations during 2011–2015 (see Fig. 1 for spatial locations). The surface water samples were collected from Sukhna Lake ($n = 65$), and check dams and ponds ($n = 81$). The groundwater sampling locations are spatially distributed across the study area. We collected groundwater samples from open wells ($n = 325$) every 15 days interval and piezometers ($n = 34$) during 2011—2014, and from tube wells ($n = 45$) during 2014–2017. The depth of open wells is up to ~ 10 m bgl, the piezometers from about 55 to ~ 65 m bgl, and tube wells from 150 to 250 m bgl.

We used pre-cleaned high-density polyethylene (HDPE) bottles (20 ml) during sampling for isotopic measurements. The bottles were rinsed twice at the sampling site with the sample water to avoid mixing and evaporative enrichment. Further, to prevent any evaporative losses from the sample bottles, bottles were tightly sealed and brought to the isotopic analysis laboratory. Additionally, we recorded geographic information (latitude, longitude, and altitude) during water sampling.

Isotopic analysis

The water samples were analyzed at the Nuclear Hydrology Laboratory at the National Institute of Hydrology, Roorkee, India. The isotopic analysis was carried out using continuous flow stable isotope ratio mass spectrometer (CFSIRMS) for $\delta^{18}O$ and dual inlet stable isotope ratio mass spectrometer (DISIRMS) for δ^2H (Epstein and Mayeda 1953, Brenninkmeijer and Morrison 1987). The results are expressed in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW) using the δ notation, which is defined as:

$$(‰) = \left(\frac{\left(R_{\text{sample}} - R_{\text{reference}} \right)}{R_{\text{reference}}} \right) \times 10^3, \tag{1}$$

where R_{sample} is the ratios of the $^{18}O/^{16}O$ and $^2H/H$ isotopes for the collected water sample, and $R_{\text{reference}}$ is the ratios of the $^{18}O/^{16}O$ and $^2H/H$ isotopes for the standard water sample. The reference standard is usually considered VSMOW. The measurement precision for $\delta^{18}O$ is $\pm 0.1‰$, and for δ^2H is $\pm 1‰$. The isotope data reported in the present study correspond to VSMOW.

Further, we used the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model devised by the NOAA Air Resources Laboratory to identify the airflow parcels in the study area. The model utilized GDAS $0.5° \times 0.5°$ meteorological data (Draxler and Hess 1998; Draxler and Rolph 2016). The backward trajectories of 500 m, 1000 m,

and 1500 m above ground level (AGL) for the total run time of 315 h were generated using the procedures described at the following web site: https://www.ready.noaa.gov/HYSPLIT_traj.php.

Results and discussion

Isotopic composition of precipitation

Measured $\delta^{18}O$ and δ^2H values of rainfall showed a marked spatial and temporal variation across the study area. The isotopic composition of rainfall for all four rain gauge stations (Kansal Log Hut, Nepli Rest House, Kansal Rest House, and Sukhna Lake at Chandigarh) ranged from $-15.9‰$ to $+7.6‰$ for $\delta^{18}O$ and $-120.0‰$ to $+64.9‰$ for δ^2H (Fig. 2). Globally, the isotopic composition of

Fig. 2 Long-term variation in $\delta^{18}O$ values of rainfall and rain amount (mm) from rain gauge stations. **a** Kansal Log Hut, **b** Kansal Rest House, **c** Nepli Rest House, and **d** Sukhna Lake from 2011 to 2015
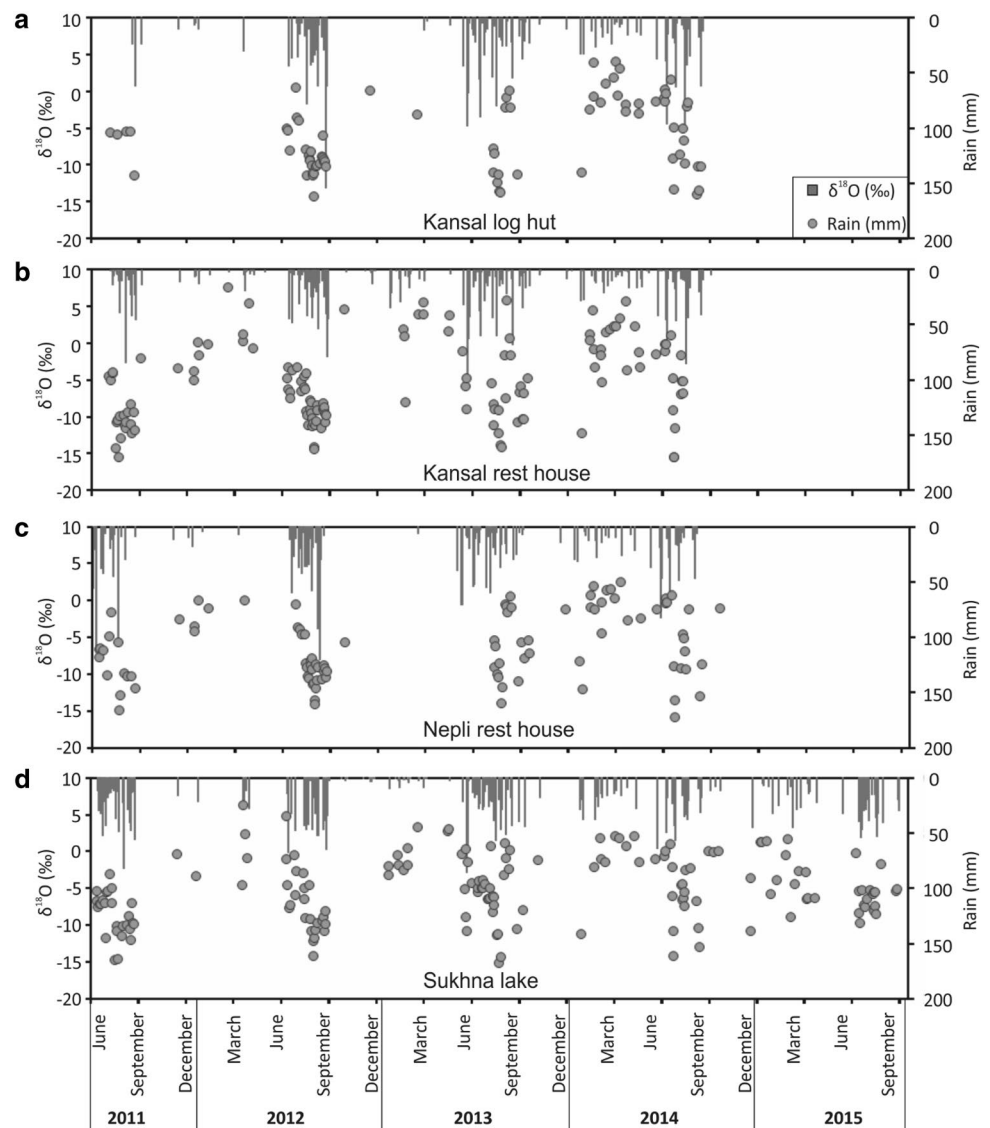
rainfall varies between -50.0‰ and $+10.0$‰ for $\delta^{18}O$ and between -350.0‰ and $+50.0$‰ for δ^2H (Hao et al. 2019). In the Ghaggar River basin, in which Sukhna Lake falls, the isotopic composition of rainfall varies from -14.8‰ to $+5.8$‰ for $\delta^{18}O$ and from -116.3‰ to $+51.5$‰ for δ^2H (Joshi et al. 2018). In the present study, the estimated amount weighted annual precipitation (AWAP) value is -6.9‰ for $\delta^{18}O$ and -46.8‰ for δ^2H for the Sukhna Lake basin. To better understand the monsoon and non-monsoon characteristics of precipitation, we also estimated the amount weighted precipitation value for the monsoon (AWMP) season, and the values are -7.8‰ for $\delta^{18}O$ and -54.6‰ for δ^2H during 2011—2015.

Figure 2a–d shows the temporal variation of $\delta^{18}O$ values of rainfall and rain amount for all four rain gauge stations. The isotopic composition of rainfall shows significantly positive $\delta^{18}O$ values (i.e., most enriched) during May–June and negative $\delta^{18}O$ values (i.e., most depleted) during August–September in all four rain gauge stations, which may be attributed to the higher temperature during the summer (May–June) and lower temperature during the monsoon season (August–September) and/or the different air mass.

A cross plot of $\delta^{18}O$ vs. δ^2H values of rainfall was prepared to obtain the local meteoric water line (LMWL) for the study area (Fig. 3). The LMWL is the best fit line prepared based on the $\delta^{18}O$ and δ^2H value of rainfall for all four gauge stations. Further, we have compared LMWL derived during the present study with the regional meteoric water line (RMWL) for the Ghaggar River basin (Joshi et al. 2018), the Indian meteoric water line (IMWL) (Kumar et al. 2010) and the global meteoric water line (GMWL) (Rozanski et al. 1993) and are given as:
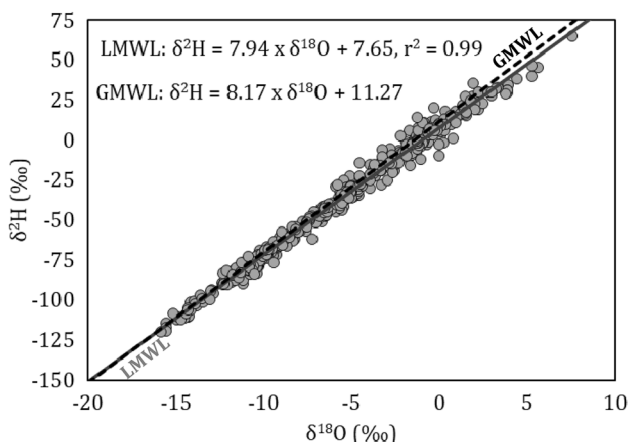
$$\delta^2H = 7.94\,(\pm 0.04) \times \delta^{18}O + 7.65\,(\pm 0.3),$$
$$\left(r^2 = 0.99\right)(\text{present study}), \tag{2}$$

$$\delta^2H = 7.9 \times \delta^{18}O + 5.56,\ \left(r^2 = 0.98\right)(\text{RMWL; Joshi et al. 2018}), \tag{3}$$

$$\delta^2H = 7.93 \times \delta^{18}O + 9.94,\ \left(r^2 = 0.98\right)(\text{IMWL; Kumar et al. 2010}), \tag{4}$$

$$\delta^2H = 8.17 \times \delta^{18}O + 11.27,\ \left(r^2 = 0.98\right)$$
$$(\text{GMWL; Rozanski et al. 1993}). \tag{5}$$

The slope of the LMWL (Eq. 2) is close to that of the RMWL (Eq. 3) and IMWL (Eq. 4) and slightly lower than that of the GMWL (Eq. 5), whereas its intercept is lower than the intercept of the IMWL as well as the GMWL. However, the intercept in the LMWL (Eq. 2) is higher than the intercept of the RMWL (Eq. 3) because Joshi et al. (2018) previously used only three monitoring stations (Sirsa, Patiala, and Chandigarh) to develop the RMWL for the Ghaggar basin. Joshi et al. (2018) also observed an evaporative isotopic signature in rainfall at Sirsa (located very close to the Thar Desert). Therefore, we found a higher intercept in Equation 2 than Equation 3 in the present study.

We also categorized the rainfall samples into three different seasons and calculated best-fit lines for data from the pre-monsoon (Eq. 6), monsoon (Eq. 7) and winter seasons (Eq. 8) to understand the seasonality in the isotopic composition of rainfall for the study region.

$$\delta^2H = 7.45(\pm 0.15) \times \delta^{18}O + 7.44\,(\pm 0.53),$$
$$\left(n = 79,\ r^2 = 0.97\right)[\text{pre - monsoon}], \tag{6}$$

$$\delta^2H = 7.95\,(\pm 0.04) \times \delta^{18}O + 7.39\,(\pm 0.33),$$
$$\left(n = 327,\ r^2 = 0.99\right)[\text{monsoon}], \tag{7}$$

$$\delta^2H = 7.64\,(\pm 0.22) \times \delta^{18}O + 9.57\,(\pm 0.98),$$
$$\left(n = 56,\ r^2 = 0.96\right)[\text{winter}]. \tag{8}$$

The slope in the best-fit line of the monsoon period (Eq. 7) is higher than that of the pre-monsoon (Eq. 6) and winters (Eq. 8), while the intercept of the monsoon and pre-monsoon period is slightly lower than that obtained from the winter data. The meteoric water line (MWL) equation for monsoon season shows that the slope is 7.95 ± 0.04, which is very close to the slope of Eqs. (3) and (5). This indicates that the rainfall in this season is not subjected to the same degree of enrichment as in other seasons and that the condensation process occurring at the lake basin is in equilibrium conditions. The lower intercept in the MWL of the monsoon

Fig. 3 Cross plot of $\delta^{18}O$ vs. δ^2H for precipitation samples (gray circles); solid gray line shows the LMWL, and the black dashed line indicates the GMWL

season (Eq. 7) compared to the GMWL indicates partial evaporation of the rainfall samples.

Isotopic composition of surface water

Isotopic composition of Sukhna Lake

The isotopic composition of Sukhna Lake water ranges from -7.4 to $+9.0‰$ for $\delta^{18}O$ and -58.5 to $+42.5‰$ for δ^2H from 2011 to 2015 (Fig. 4). We observed depleted $\delta^{18}O$ and δ^2H value in Sukhna Lake water during the monsoon season, which can be attributed to the effects of rainfall and surface runoff. A few water samples show depleted isotopic signature during January 2012 and 2014, and June 2014, possibly due to the effect of direct precipitation over the Sukhna Lake basin. During the pre- and post-monsoon season, the Sukhna Lake water shows progressively enriched isotopic signature due to the evaporation effect.

Isotopic composition of surface water bodies

The study area is characterized by several small surface water bodies (check dams and ponds). The Sukhna Lake is much bigger than the other surface water bodies present in the study area; therefore, we established two separate regression lines for the Sukhna Lake water line (SLWL: Eq. 9) and ponds and check dams water line (PDWL: Eq. 10) (Fig. 5). The equations are as follows:

$$\delta^2H = 5.87(\pm 0.1) \times \delta^{18}O - 9.63(\pm 0.35), r^2 = 0.98 \,(\text{SLWL}), \quad (9)$$

$$\delta^2H = 5.14(\pm 0.1) \times \delta^{18}O - 17.77(\pm 0.61), r^2 = 0.97 \,(\text{PDWL}). \quad (10)$$
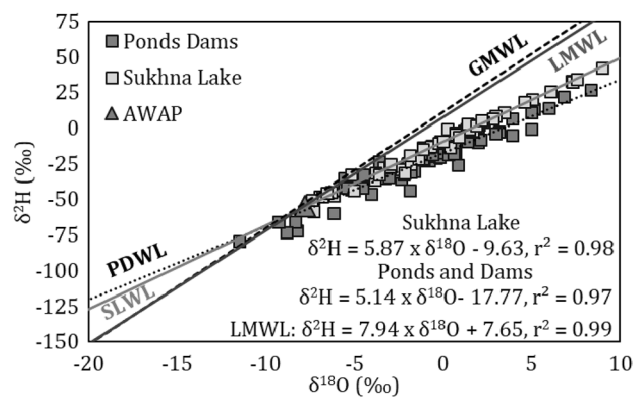
Fig. 5 Cross plot of $\delta^{18}O$ vs. δ^2H for Sukhna Lake (light gray squares), and surface water (ponds and check dams) samples (dark gray squares); solid gray line shows the LMWL, and the black dashed line shows the GMWL. The light gray line shows the Sukhna Lake water line (SLWL). The black small dotted line indicates the ponds and dams water line (PDWL)

The slope and intercept of SLWL and PDWL are less than those of LMWL, suggesting a strong evaporation impact in the Sukhna Lake water and surface water bodies. The SLWL and PDWL lines pass through the AWAP, indicating precipitation is the primary source of water in the Sukhna Lake and other surface water bodies (Fig. 5). However, different slopes in both regression lines (Eqs. 9 and 10) show variability in evaporation rates, mainly caused by the variable morphometric conditions of the water bodies. In general, the effects of evaporation on the isotopic composition of the water are greater in the smaller and more shallow water bodies compared with Sukhna Lake.
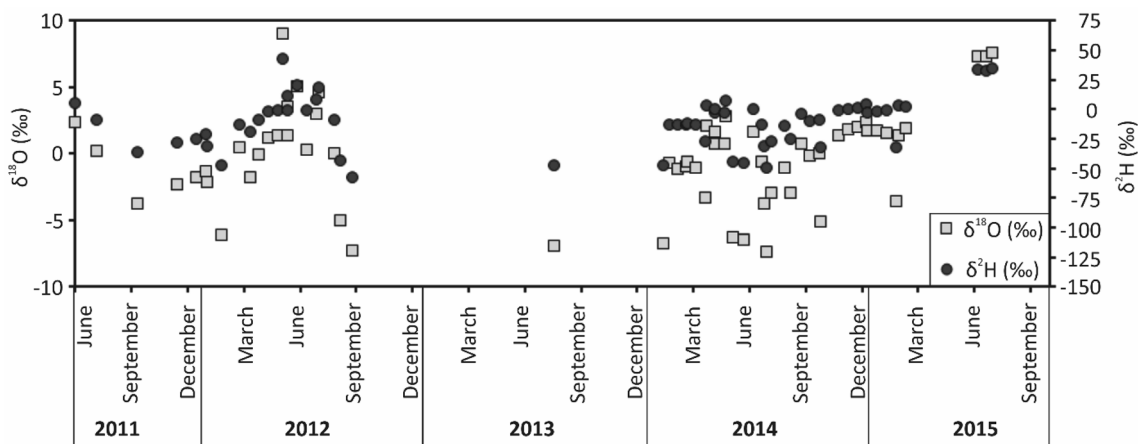
Fig. 4 Temporal variation of $\delta^{18}O$ and δ^2H values of Sukhna Lake water from 2011 to 2015. Gray squares show $\delta^{18}O$ values, and black circles show δ^2H values of Sukhna Lake water
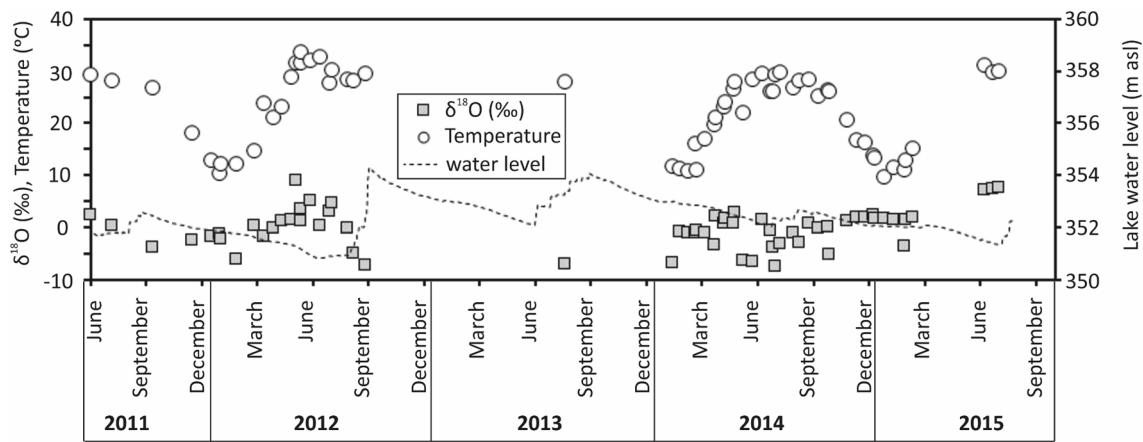
Fig. 6 Temporal variation in $\delta^{18}O$ values of Sukhna Lake water, air temperature, and Sukhna Lake water level in the study area

Relationship between lake water level and temperature with δ18O value of Sukhna Lake

Figure 6 shows the seasonal variations of lake water levels, temperature, and $\delta^{18}O$ values in the Sukhna Lake. We observed that there were enriched $\delta^{18}O$ values in Sukhna Lake during June and depleted values during September. The Sukhna Lake water level is higher during September and lower during June (Fig. 6). We found an inverse correlation between the $\delta^{18}O$ value of Sukhna Lake and water levels. The maximum depleted $\delta^{18}O$ value occurs during September because of rainfall contribution and lower temperature. In contrast, the most enriched $\delta^{18}O$ value occurs during June due to the effects of evaporative enrichment and higher temperatures.

Isotopic composition of groundwater

The isotopic composition of groundwater varies significantly across the study area (Table S1). Measured $\delta^{18}O$ and δ^2H values of groundwater show spatial and depth-related variation in Aquifer-I and II. Further, we have categorized groundwater samples based on aquifer system in the study area: (a) Aquifer-I: zone-1a (depth generally above 10 m bgl), and zone-1b (depth generally between 55 and 65 m bgl), and (b) Aquifer-II: zone-2 (depth generally between 150 and 250 m bgl).

Groundwater zone-1a

The isotopic composition of groundwater shows a large degree of spatial and temporal variability across the study area, and ranges from -2.2 to $-8.2‰$ (average: $-5.7‰$) for $\delta^{18}O$, and from -23.2 to $-60.5‰$ (average: $-41.2‰$) for δ^2H in zone-1a (Table 1). We prepared a cross plot between $\delta^{18}O$ and δ^2H values of open wells (Fig. 7a), which shows most of the groundwater samples fall on or along the LMWL, suggesting rainfall is the primary recharge source for these samples. On the other hand, most of the groundwater samples from Nepali Rest House, Naththawala and Kansal Log Hut sites fall below the LMWL, suggesting evaporative enrichment during recharge processes and/or mixing between surface water and groundwater in the study area.

The enriched isotopic values of groundwater in zone-1a may be due to the recharge from rain and/or seepage from surface water bodies in the upstream region of the study area. For example, the $\delta^{18}O$ value of groundwater ranges from -2.2 to $-7.3‰$ at the Kansal Log Hut site, suggesting

Table 1 Summary of $\delta^{18}O$ and δ^2H values of open well data

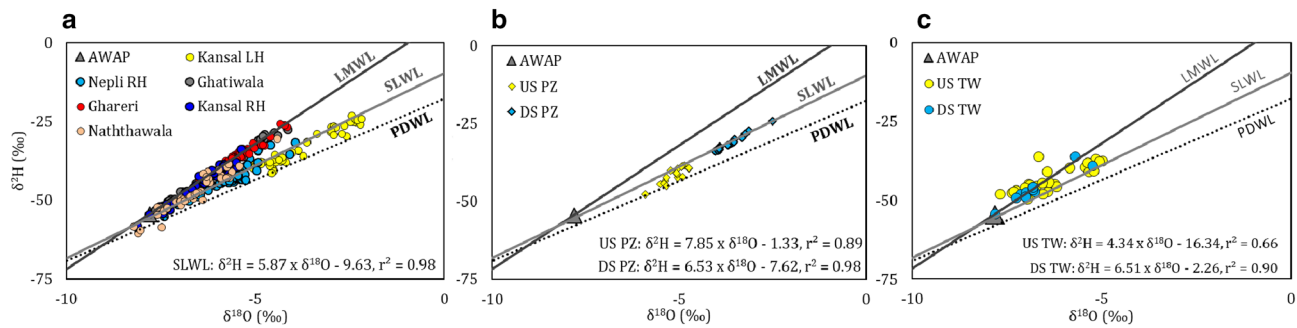| SN	Locations	$\delta^{18}O$ (‰)			δ^2H (‰)		
		Minimum	Maximum	Average	Minimum	Maximum	Average
1	Kansal Log Hut	-7.3	-2.2	-4.2	-51.2	-23.2	-35.2
2	Kansal Rest House	-8.1	-5.4	-6.6	-58.0	-33.8	-45.6
3	Nepli Rest House	-7.4	-4.0	-5.6	-55.2	-31.7	-42.5
4	Naththawala	-8.2	-4.4	-6.6	-60.5	-30.5	-47.2
5	Ghareri	-6.5	-4.2	-5.3	-42.1	-25.8	-35.2
6	Ghatiwala	-7.7	-4.1	-6.2	-53.2	-27.4	-41.6

Fig. 7 Cross plot of $\delta^{18}O$ vs. δ^2H for groundwater samples **a** zone-1a (depth up to 10 m bgl), sampling location shown by circles; Nepli Rest House (RH: blue circles), Ghareri (red circles), Naththawala (orange circles), Kansal Log Hut (LH: yellow circles), Ghatiwala (gray circles), and Kansal Rest House (RH: blue circles); **b** zone-1b (depth between 55 and 65 m bgl), sampling locations shown by squares; Upstream piezometer (US PZ) locations shown in yellow squares and downstream piezometer (DS PZ) locations shown in blue squares, and **c** zone-2 (depth between 150 and 250 m bgl), sampling locations shown by circles; Upstream tube wells (US TW) locations shown in yellow circles and downstream tube wells (DS TW) locations shown in blue circles. The amount weighted average precipitation (AWAP) is shown in a gray triangle. The black small dotted line shows the ponds and dams water line (PDWL). The light gray continuous line shows the Sukhna Lake water line (SLWL). The dark gray continuous line shows LMWL

that the groundwater samples from zone-1a in this area are recharged by rain and other sources. On the other hand, in the locations where there are no significant variations, but the isotopic signatures are depleted, the recharge could be only due to rainfall. For example, the variations in $\delta^{18}O$ values at Kansal Rest House are not significant and range from − 6.0 to − 8.0‰. However, if there are no substantial variations but the isotopic signatures are enriched, the recharge is mostly from rainfall, but there is some contribution from the surface water bodies, as in Ghareri, where the variations are in the range of − 4.2 to − 6.5 for $\delta^{18}O$.

The isotopic signature of groundwater in zone-1a at the Kansal Rest House, Ghareri, and Ghatiwala sites mostly plot on the LMWL (Fig. 7a), suggesting precipitation is the primary recharge source for these locations. The groundwater in zone-1a at the Kansal Log Hut, Nepli Rest House and Naththawala sites follow the PDWL in the lake basin, indicating that the significant recharge to groundwater at these locations could be from enriched surface water bodies like check dams and ponds nearby. It can also be understood from groundwater enrichment that the magnitude of recharge is different at different locations. In general, groundwater in the lake basin gets recharged through rain (Joshi et al. 2018) and surface water bodies, suggesting that the groundwater system is hydraulically connected in the study region (Shekhar et al. 2020; van Dijk et al. 2020).

Groundwater zone-1b

We have measured the isotopic composition of two piezometers in zone-1b. Piezometer-1 is located in the downstream region, and Piezometer-2 is located in the upstream region of the Sukhna Lake in the study area (see Fig. 1c for spatial location). The isotopic composition of Piezometer-1

varies from − 4.0 to − 2.5‰ (average: − 3.6‰) for $\delta^{18}O$, and from − 33.9 to − 24.2‰ (average: − 31.1‰) for δ^2H, and for Piezometer-2 values varies from − 5.9 to − 4.7‰ (average: − 5.1‰) for $\delta^{18}O$, and from − 47.7 to − 38.6‰ (average: − 41.7‰) for δ^2H for the period of 2014–2017. A cross plot of $\delta^{18}O$ vs. δ^2H values of groundwater shows enrichment toward the downstream region (Fig. 7b). Further, we have plotted two regression lines for both piezometers to understand the spatial variability in the isotopic composition of the upstream and downstream regions in the study area. The regression line for Piezometer-2 is (US PZ: upstream Piezometer): $\delta^2H = 7.85 \times \delta^{18}O − 1.33$ (r^2: 0.89), and for Piezometer-1 is (DS PZ: downstream Piezometer) $\delta^2H = 6.53 \times \delta^{18}O − 7.62$ (r^2: 0.98). The slope and intercept in both the groundwater regression lines are lower than those of the LMWL, suggesting evaporation in groundwater samples. The groundwater samples from Piezometer-1 fall on or along the SLWL and from Piezometer-2 vary between PDWL and SLWL (Fig. 7b) due to the different recharge conditions and mechanisms in the study area. It can be observed that there are mainly two recharge sources for the groundwater system: (1) rainfall and (2) surface water bodies (seepage from check dams and ponds).

Groundwater zone-2

Measured isotopic composition of groundwater in zone-2 ranges from − 5.0 to − 7.8‰ (average: − 6.5‰) for $\delta^{18}O$ and from − 54.4 to − 36.2‰ (average: − 44.8‰) for δ^2H from 2011–2014 (Table S1). The isotopic values in most groundwater samples in zone-2 fall on the LMWL (Fig. 7c), suggesting precipitation is the primary recharge source for the deeper zone in the study area (Joshi et al. 2018). Further, we have plotted two regression lines for both upstream

and downstream tube wells to understand the study area's recharge processes. The regression line for the upstream region (US TW: upstream tube wells) is $\delta^2H = 4.34 \times \delta^{18}O - 16.34$ (r^2: 0.66), and for downstream region (DS TW: downstream tube wells) is $\delta^2H = 6.51 \times \delta^{18}O - 2.26$ (r^2: 0.90). The slope in both the regression line is lower than that of the LMWL and GMWL. The intercept of the regression line is more negative in the upstream region compared to the downstream region.

Deuterium excess and its hydrological significance

The deuterium excess (d-excess) is primarily a function of atmospheric relative humidity, wind speed, and air temperature that can be defined as $d = \delta^2H - 8 \times \delta^{18}O$ (Dansgaard 1964) and can be thought of as an index of deviation from the GMWL, which has a d-excess value of 10‰. The d-excess value in regional rain can be > 10 if the source region's evaporation occurs under lower humidity (Rozanski et al. 1993; Kamtchueng et al. 2015). The d-excess means surplus deuterium relative to Craig's GMWL line (Craig 1961; Dansgaard 1964; Craig and Gordon 1965). This means that the magnitude of equilibrium fractionation (condensation) for δ^2H is about eight times that of $\delta^{18}O$. The d-excess can be correlated with conditions at the source area for the water vapor in an air mass and the nature of the air mass before the moisture falling as rain or snow (Clark and Fritz 1997; Froehlich et al. 2002; Benjamin et al. 2005).

d-Excess of precipitation and vapor source identification

The d-excess values of rainfall vary seasonally across the study area and range from -3.5 to $+19.5‰$ (average $+7.8‰$) for the pre-monsoon season, from -3.5 to $+15.0‰$ (average $+7.8‰$) for the monsoon season, from -3.9 to $+15.7‰$ (average $+6.3‰$) for the post-monsoon season, and from -5.4 to $+24.2‰$ (average $+10.4‰$) for the winter season. The d-excess value of rainfall is higher during winters than pre-monsoon, monsoon, and post-monsoon seasons, suggesting different precipitation sources. As mentioned earlier, the d-excess values $> 10‰$ occur when evaporation in the source region takes place under conditions of lower humidity, and such d-excess values are mostly found for the rainfall during winter (Rozanski et al. 1993; Kamtchueng et al. 2015; Lone et al. 2019).

To understand the study area's vapor sources, we selected a few major rainfall events from 2011 to 2014 for backward trajectory analysis. We plotted backward trajectories for airflows using the HYSPLIT model at 500 m, 1000 m, and 1500 m aboveground level (AGL) for the study region (Fig. 8). The winter airflow trajectories show that the vapor source is mainly dominated by high d-excess values, suggesting that moisture is brought into the study area by

westerly winds during the winter season (Fig. 8a, d) (Liu et al. 2008a, 2008b; Jeelani et al. 2013, 2017;; Lone et al. 2019). The higher relative humidity over the Arabian Sea and Bay of Bengal during the summer season gives rise to lower d-excess values in rainfall (Kumar et al. 2010; Jeelani et al. 2017). This type of d-excess values observed during summer and the monsoon season is due to a vapor source associated with the southwest monsoon (Fig. 8b–c, e–f). In general, we found that there were two principal vapor sources for rainfall in the study region. These are from (a) westerly air masses and (b) from the southwest monsoon. Additionally, local moisture recycling is also likely to play an important role during precipitation events in the study area.

d-Excess of surface water

A cross plot of d-excess vs. $\delta^{18}O$ values of surface water is presented in Fig. 9a, b. The d-excess values of Sukhna Lake range from -29.5 to $+8.8‰$ (average: $-9.5‰$) and from -82.6 to $+12.5‰$ (average: $-17.9‰$) for the other surface water bodies. The isotopic composition of surface water bodies in the region are strongly affected by evaporation during the pre-monsoon season, possibly due to the hot weather conditions. During the monsoon, the lake d-excess values are comparatively higher than in the pre-monsoon season because of the effects of monsoon rainfall, which mixes with the highly evaporative surface water bodies and increases the d-excess value of surface water bodies. After the monsoon is finished, d-excess values decrease due to the evaporation process, which starts enriching the lake's water and other water bodies in the basin. The d-excess value of other surface water bodies has significantly lower values than the Sukhna Lake, suggesting that the evaporation effect and/or mixing between surface water and groundwaters is more significant in the surface water bodies compared to the Sukhna Lake in the study area.

The seasonal variation in the isotopic composition of Sukhna Lake and other surface water bodies in the study area is indicative of a short residence time for the water (Jonsson et al. 2009). Since the lake has significant evaporation, most of the water leaves the lake by the end of the water year, and by the end of summer, only an insignificant amount of water is left in the lake (Khobragade et al. 2013). The lake gets replenished every year during the monsoon season. This implies shorter residence times of the lake water. The same is true for the water bodies in the basin where most of the water gets lost due to evaporation, and the water bodies are replenished every year with monsoon rainfall. Due to the short residence time, the lake and other water bodies cannot achieve equilibrium conditions on an annual scale.
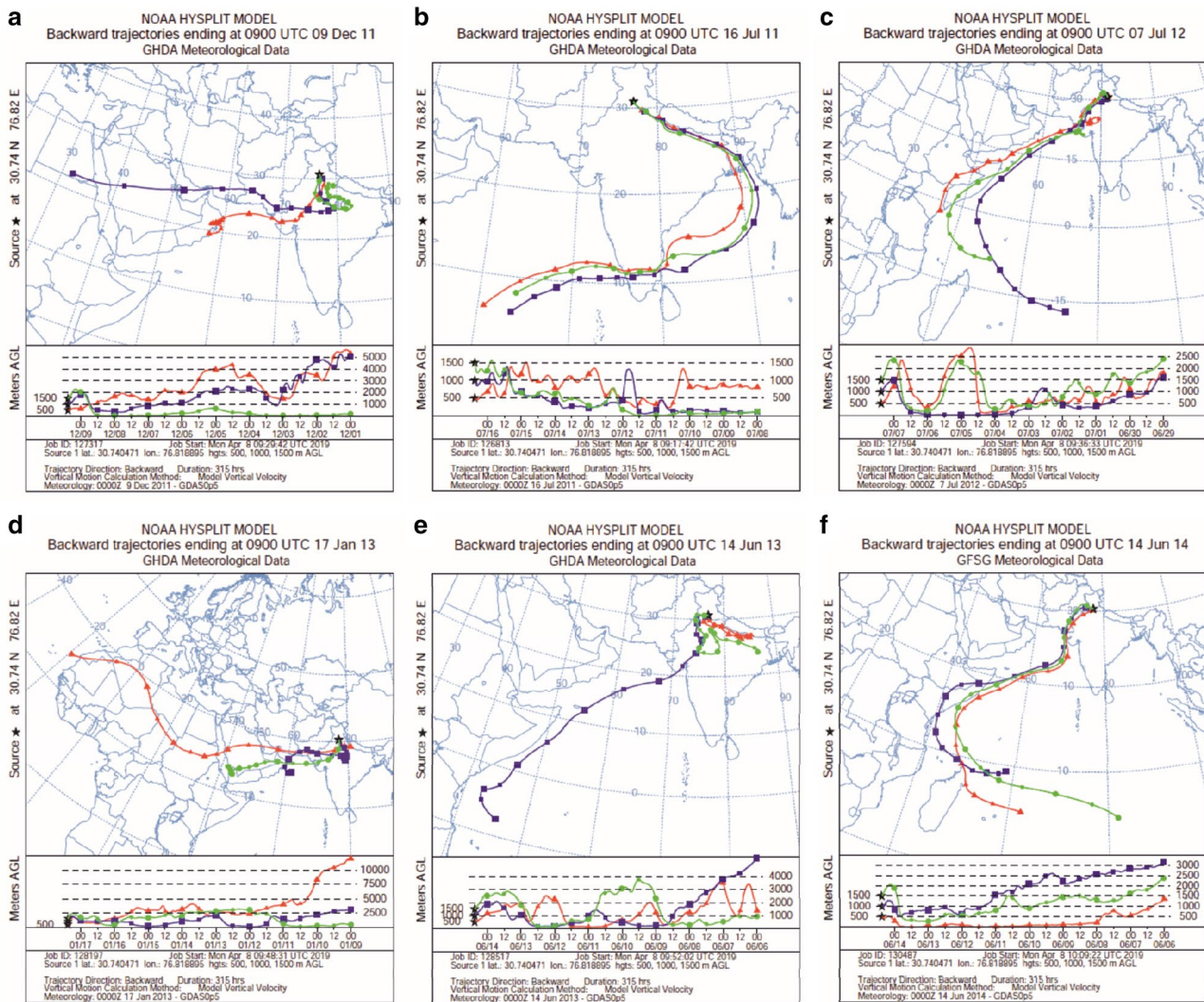
Fig. 8 Backward trajectory during significant rainfall events in the study region for the period of **a** December 2011, **b** July 2011, **c** July 2012, **d** January 2013, **e** June 2013, and **f** June 2014
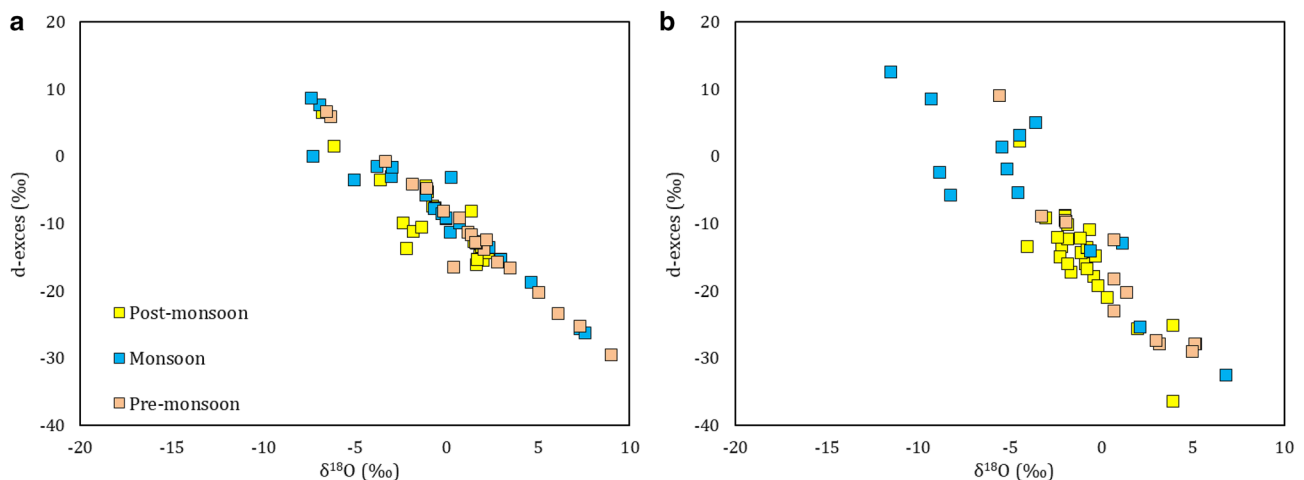

Fig. 9 Cross plot of $\delta^{18}O$ vs. d-excess during pre- and post-monsoon and monsoon season; **a** Sukhna Lake water and **b** ponds and check dams

The d-excess of groundwater

The d-excess value of groundwater shows a marked spatial and temporal variation across the study area (Table S1). The d-excess values of groundwater in zone-1a ranges from -9.1 to $+9.7‰$ (average: $+4.5‰$), and for rainfall -5.4 to $+24.2‰$ (average: $+8.0‰$). The d-excess of groundwater is comparatively lower than that of rainfall in the study region. However, it is much higher than the d-excess value ($-17.9‰$) of the various surface water bodies (ponds and check dams) in the study area. This indicates that the groundwater in zone-1a receives a significant amount of recharge by seepage from the surface water bodies in the downstream region. The d-excess value of piezometers ranges from -4.2 to $-1.2‰$ (average: $-2.3‰$) for Piezometer-1 and from $-2.9‰$ to $+1.4‰$ (average: $-0.6‰$) for Piezometer-2 in groundwater in zone-1b and shows lower d-excess value compared to the rain. This suggests that groundwater in zone-1a gets a significant amount of recharge through the enriched surface water, but the groundwater in zone-1b gets recharged through enriched surface water. This suggests a similarity in aquifer characteristics and recharge sources of groundwater. Joshi et al. (2018) also suggested active recharge conditions in groundwater (depth generally above 80 m bgl) for the Ghaggar basin.

The d-excess value of groundwater in zone-2 varies from $+0.9$ to $+17.1‰$ (average: $+7.5‰$) and is very close to the d-excess value of rain in the study area. Similar results have been reported by Joshi et al. (2018) for the Ghaggar basin. They suggested a single recharge source and regional flow system in groundwater (depth generally below 80 m bgl) for northwest India. Our results also show similar findings, which suggest precipitation is the primary recharge source for groundwater in zone-2 in the study area.

Groundwater recharge and its dynamics

To understand the recharge sources for groundwater in zone-1a in the study region, the d-excess values of rainfall, groundwater from zone-1a, and various surface water bodies such as check dams and ponds have been plotted in Fig. 10. It was observed that most of the groundwater samples in zone-1a plot on or close to the rainfall line, while a few samples have an isotopic composition very close to the surface water bodies. This suggests that the groundwater in zone-1a mainly gets recharged from rainfall and, to some extent, from surface water bodies. A few groundwater samples in zone-1a follow the d-excess value of surface water during the pre-monsoon season, while the occurrence of groundwater in zone-1a in surface water d-excess increases with the monsoon and post-monsoon seasons. During the pre-monsoon season, most of the smaller surface water bodies generally become dry, and only a small
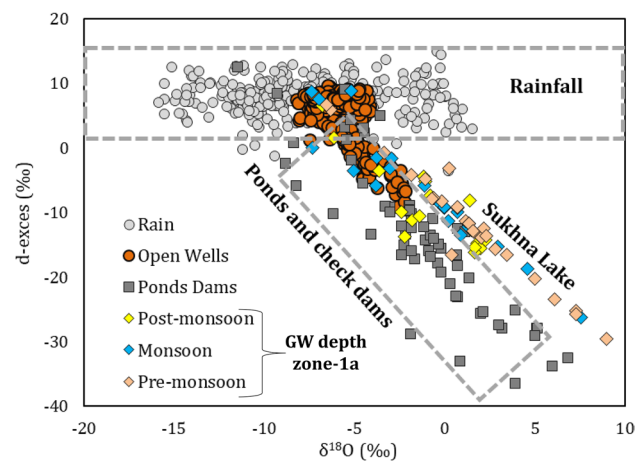

Fig. 10 Cross plot of $\delta^{18}O$ vs. d-excess of rainfall (gray circles), ponds and check dams (gray squares), and open wells in zone-1a (dark orange circles), and Sukhna Lake water during pre- and post-monsoon and monsoon season

quantity of water is available in the larger water bodies in the study area. As such, not much water is available in these water bodies to recharge the groundwater. Therefore, during the pre-monsoon season, the d-excess value of a few groundwater samples in zone-1a is very similar to that of the surface water bodies. During the monsoon season, most of the surface water bodies are filled with water and hence recharge of groundwater starts increasing. The increased recharge rate during the post-monsoon months compared to the monsoon months is mainly due to the recharge from delayed flow from surface water bodies.

Spatially, groundwater d-excess values from zone-1a at the Naththawala and Kansal Rest House sites are slightly lower than those of the rain. This suggests that although the groundwater samples in zone-1a at Naththawala and Kansal Rest House are predominantly recharged by infiltrating rainfall, a small proportion of the recharge is derived from seepage from surface water bodies. The data from the Kansal Log Hut and Nepli Rest House sites suggest that the proportion of recharge that is derived from seepage is very small.

The d-excess values of groundwater in zone-1a at the Ghareri and Ghatiwala sites are very similar to that of the average value of rain. This suggests that the recharge source at these locations is precipitation, with negligible recharge from the nearby surface water bodies.

A cross plot of $\delta^{18}O$ vs. d-excess shows the relationship between various water sources in the study area (Fig. 10). This suggests precipitation is the primary recharge source for Sukhna Lake, groundwater in zone-1a, and surface water bodies in the study area. The lake water samples were categorized in pre-monsoon, monsoon, and post-monsoon seasons to better understand the lake water's seasonality. It is observed that a few samples of lake belonging to the

monsoon and post-monsoon months have a similar relationship of d-excess and $\delta^{18}O$, as those of the surface water bodies in the basin suggest that the lake also receives some water from surface runoff. Further, it is observed that groundwater in zone-1a shows a similar trend of d-excess values to surface water bodies in the basin.

Conclusions

Isotopic analyses of surface water (Sukhna Lake, ponds, and check dams), rainfall, and groundwater samples show that the stable isotopic composition of water in the study area varies seasonally. Our results suggest that the surface water is mainly replenished by precipitation. The primary recharge source for Sukhna Lake is precipitation and surface runoff generated through local rainfall. We observed that there was a westerly source of vapor for precipitation events in winters in the study area, rather than from a southerly source during the southwest monsoon season. Our results suggest the evaporation effect in the Sukhna Lake and other surface water bodies. The variation in the isotopic composition of surface water is also indicative of short residence time. It can be concluded that the surface water cannot achieve equilibrium conditions at an annual scale. The groundwater depth zone-1a and 1b is mainly recharged by local precipitation and seepage from surface water bodies, suggesting evaporative enrichment during the recharge processes. The groundwater samples in zone-1b show a significant contribution from surface water bodies in the study area's upstream region, but mixing in the study area's downstream region. The groundwater in zone-2 is mainly recharged by precipitation and regional flow system. Our results also suggest two types of groundwater flow pattern present in the study area: local flow system that can be seen in zone-1a and b, and regional flow system in zone-2.

Author contributions SKJ designed and conceptualized the manuscript. PS was involved in field data collection and wrote the initial draft. SKJ, PS analyzed the isotopic data. SKJ contributed to the interpretation with PS, SDK. SKJ wrote the final draft with an important contribution from PS, SDK. All authors provided input to analysis and interpretation.

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