

# Isotope techniques to identify recharge areas of springs for rainwater harvesting in the mountainous region of Gaucher area, Chamoli District, Uttarakhand

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Environmental isotope techniques have been employed to identify the recharge areas of springs in India, in order to construct artificial recharge structures for rainwater harvesting and groundwater augmentation for their rejuvenation. A model project was taken up in the mountainous region of Gaucher area, Chamoli District, Uttarakhand for this purpose. The springs in this region are seasonal and are derived from seepage waters flowing through the shallow weathered and fractured zone. The chemistry of high-altitude springs is similar to that of precipitation, whereas water-rock interactions contributes to increased mineralization in low-altitude springs. The stable isotopic variation in precipitation suggests that the altitude effect for Gaucher area is  $-0.55\%$  for  $\delta^{18}\text{O}$  and  $-3.8\%$  for  $\delta^2\text{H}$  per 100 m rise in altitude. Based on local geology, geomorphology, hydrochemistry and isotope information, the possible recharge areas inferred for valleys 1, 2 and 3 are located at altitudes of 1250, 1330 and 1020 m amsl respectively. Water conservation and recharge structures such as subsurface dykes, check bunds and contour trenches were constructed at the identified recharge areas in the respective valleys for controlling the subsurface flow, rainwater harvesting and groundwater augmentation respectively. As a result, during and after the following monsoon, the discharge rates of the springs not only increased significantly, but also did not dry up even during the dry period. The study shows that the isotope techniques can be effectively used in identifying recharge areas of springs in the Himalayan region. It also demonstrates the advantage of isotope techniques over conventional methods.

**Keywords:** Environmental isotopes, rainwater harvesting, recharge, springs.

THE available freshwater in India is less than the estimated water supply required for meeting the ever-increasing

demand. Millions of people lack access to safe drinking water and its scarcity is more acute in the arid, semi-arid and mountainous regions of the country. Water resources in these regions are often restricted to groundwater. The groundwater is dynamic and replenishable, but is a limited resource. It is recharged directly by local precipitation or through soil and weathered zones from remote distant outcrops (recharge areas). In order to cater to the increasing water demand, rainwater harvesting is being practised in recent years for augmenting and managing the existing groundwater resources. Identification of source and origin of groundwater is of importance for systematic planning of water-conservation measures to sustain the current and future levels of the water resource development.

In the mountainous region of Gaucher area, Uttarakhand, springs are the only available source of water for domestic, agricultural and other uses. These resources are meagre and low discharges during summer cause a lot of hardship to the people. Hence, a model project was taken up to identify the recharge area of springs in the Gaucher area using environmental isotope techniques for rejuvenation of these drying springs.

There are a number of conventional methods available to study the hydrological processes<sup>1</sup>, but these methods cannot always address all aspects of the system. Environmental and artificial radioactive isotope techniques have proved to be effective tools for solving many critical hydrological problems and in many cases, provide information that could not be obtained by any other means<sup>2-4</sup>. However, use of environmental isotopic techniques in conjunction with conventional hydrogeology and geochemistry would be more productive. Environmental isotopes (stable and radioactive) have a distinct advantage over artificial tracers as they facilitate the study of various hydrological processes on a much larger temporal and spatial scale through their natural variation in a system. The use of artificial tracers is generally effective for site-specific and local applications<sup>5-7</sup>.

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## Fundamentals of isotope hydrology

The most frequently used environmental isotopes for hydrological investigations include isotopes of elements of the water molecule [ $^1\text{H}$  (protium),  $^2\text{H}$  (deuterium),  $^3\text{H}$  (tritium),  $^{16}\text{O}$  and  $^{18}\text{O}$ ] and that of the element carbon [ $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{14}\text{C}$ ] occurring in water as constituents of dissolved inorganic and organic compounds. Applications of stable isotope ratios of hydrogen and oxygen in groundwater are based primarily upon isotopic variations in precipitation. Radioactive isotopes originated from cosmogenic nuclear reactions and atmospheric nuclear testing that took place up to the early 1960 are useful for age determination of groundwater.

Environmental isotope techniques help in understanding the source and mechanism of recharge<sup>8–10</sup>, groundwater circulation and its renewability<sup>11,12</sup>, recharge areas and transit times of the aquifer<sup>13,14</sup>, hydraulic inter-relationships<sup>15,16</sup>, and source and mechanism of groundwater contamination<sup>17–19</sup>.

Stable isotope compositions are generally reported as  $\delta$  values in parts per thousand (‰). The  $\delta$  values are given by

$$\delta^2\text{H}(\text{or } \delta^{18}\text{O}) = \frac{R_{\text{SAMPLE}} - R_{\text{STANDARD}}}{R_{\text{STANDARD}}} \times 10^3,$$

where  $R$  represents the ratio of heavier to lighter isotope ( $^2\text{H}/^1\text{H}$  or  $^{18}\text{O}/^{16}\text{O}$ ).  $R_{\text{SAMPLE}}$  and  $R_{\text{STANDARD}}$  are the isotope ratios in the sample and the standard respectively.  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values are reported relative to Standard Mean Ocean Water (SMOW). The sample is termed as depleted if the  $\delta$  values are lower, and as enriched if the  $\delta$  values are higher with respect to a reference.

Stable isotopic composition of water ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) is modified by processes like evaporation and condensation, and hence the recharge water in a particular environment will have a characteristic isotopic signature. This signature serves as a natural tracer for water movement. Globally,  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  of precipitation show good correlation given by<sup>20</sup>:

$$\delta^2\text{H} = 8 * \delta^{18}\text{O} + 10. \quad (1)$$

This equation is called Global Meteoric Water Line (GMWL). Variation in local climatic conditions and source of the moisture affect the isotopic composition of precipitation, and therefore the local meteoric water line (LMWL) needs to be constructed for each location under study<sup>21</sup>.

The application of stable isotopes to recharge problems is based on the spatial and temporal variation of the isotopes of elements of the water molecules. As water evaporates from the ocean surface, the lighter isotopes ( $^1\text{H}$  and  $^{16}\text{O}$ ) preferentially move to the vapour phase because of the difference in vapour pressures and diffusion velocities, and the resulting vapour mass is depleted in heavier isotopes ( $^2\text{H}$  and  $^{18}\text{O}$ )<sup>22</sup>. When vapour mass condenses, these heavier isotopes get enriched in rain compared to the

remaining vapour<sup>23</sup>. The former process takes place under non-equilibrium condition (kinetic effect), whereas the latter process occurs under equilibrium condition (thermodynamic effect). The kinetic fractionation for  $^{18}\text{O}$  is more than that of  $^2\text{H}$ , and the degree of fractionation depends on temperature and relative humidity.

The isotopic composition of precipitation is affected by season, latitude, altitude, amount and distance from the coast. The seasonal variation in temperature at a particular location generates strong seasonal variation in isotope composition of precipitation, with more depleted values occurring in the colder months than in summer<sup>24</sup>. This variation acts as a tool to determine the time during the year when most recharge occurs in aquifers. Precipitation occurring at higher latitudes (Polar regions) is more depleted in isotopic composition compared to tropical regions. This latitude effect is due to successive rainouts from the cloud during moisture transport from the tropics to the poles. A latitude effect of  $-0.6\text{‰}$  for  $\delta^{18}\text{O}$  per degree is generally observed<sup>24</sup>. The heavier isotopes in precipitation generally decrease with distance from the coast. When moist air mass originating from the ocean condenses near the coast, it will have an isotopic composition similar to that of sea water. As the air mass moves inland, the vapour gets continuously depleted in the heavier isotopes due to the rainout process (continental effect)<sup>25</sup>. Heavy rainfall is depleted in isotopic composition compared to light rain (amount effect). The amount effect results in an average depletion of  $-1.5\text{‰}$  in  $\delta^{18}\text{O}$  per 100 mm of rainfall<sup>26</sup>. This is partly due to evaporation of falling raindrops and also due to exchange with atmospheric water vapour during light rain. It is also possibly due to removal of different amounts of water from the atmosphere<sup>27</sup>. In regions with altitude difference, orographic precipitation occurs as vapour mass rises over the landscape. Hence at higher altitudes, where average temperatures are lower, precipitation will be isotopically depleted compared to the lower altitudes. In the atmosphere, cooling of saturated air mass causes condensation and it releases some heat counteracting the cooling. This temperature change with altitude is called 'wet adiabatic lapse rate'. The wet adiabatic lapse rate varies with altitude and is about  $0.6^\circ\text{C}$  per 100 m. Since the isotopic composition is temperature-dependent, the isotopic composition of precipitation depletes with altitude. The altitude effect generally varies from  $-0.15$  to  $-0.5\text{‰}$  for  $\delta^{18}\text{O}$  and from  $-1$  to  $-4\text{‰}$  for  $\delta^2\text{H}$  per 100 m rise in altitude<sup>24</sup>. This altitude effect was used to identify the recharge areas in several hydrological investigations<sup>28,29</sup>. In the present study, altitude effect has been utilized to identify the recharge areas to the springs in Gaucher area, Chamoli District, Uttarakhand.

## Study area

Gaucher area is located about 300 km away from Dehradun, in the Dehradun–Badrinath road at lat.  $79^\circ 5' - 79^\circ 8' \text{E}$

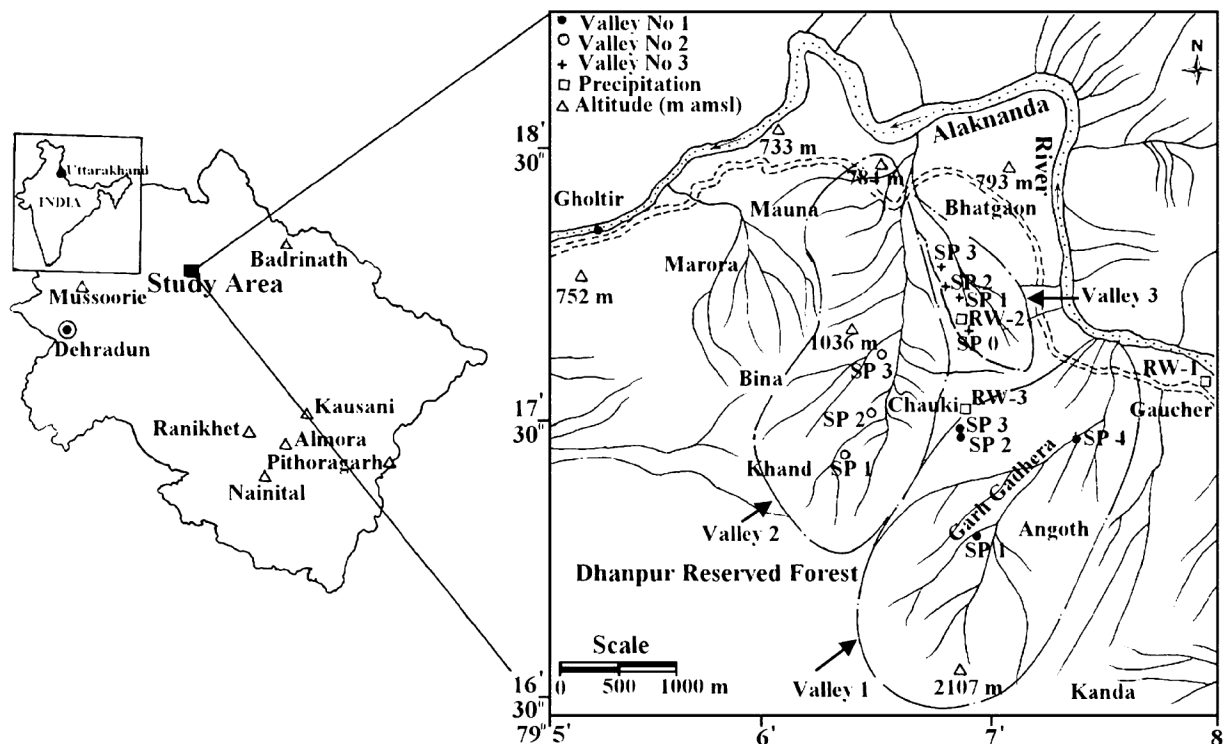


Figure 1. Location map of the study area with sampling points.

and long.  $30^{\circ}16' - 30^{\circ}18'N$ . The minimum and maximum topographic altitudes of this area are 800 and 2100 m amsl respectively. The area receives an average annual rainfall of about 800 mm, which occurs during the months of July–September. Many springs exist in the valleys of this mountainous region and they are the main sources of water for domestic as well as agricultural use. Eleven springs located in three valleys, viz. valleys 1, 2 and 3 were monitored for the study (Figure 1). Valley-1 slopes in the W–E direction, whereas valleys 2 and 3 are towards SSW–NNE and SE–NW respectively. The springs are seasonal with high discharges during monsoon and dry during summer.

### Geological setting

The study area is part of the Rudraprayag Formation of the Garhwal Group, which belongs to Late Precambrian to Cambrian age. The lithostatigraphy of this formation is divided into Uttyasu Quartzite, Lameri Member, Haryali Quartzite, Thallassu Schistose Grit and the Karanprayag Metavolcanics in succession<sup>30</sup>. Haryali quartzite of Rudraprayag Formation occupies a greater part of the area and is characterized by epidiorite/chlorite schist. Thalassu Schistose Grit is composed of Schistose Grit with basic dykes, purple and greenish-grey and green phyllite, gritty to conglomerates, banded white and purple, and maroon quartzite with beds of purple slate. The area is tectonically disturbed with faults and folds.

### Sampling and measurement

Monthly discharge rates of all springs were measured during December 2003–April 2006. Locations of springs are given in Figure 1. Water samples collected from the springs (four springs from valley-1, three from valley-2 and four from valley-3) and precipitation during September 2004 were analysed for environmental isotopes such as  $^2H$ ,  $^{18}O$  and  $^3H$  as well as hydrochemistry.

The physical parameters like pH, electrical conductivity and temperature were measured *in situ* using Eutech instrument cyberscan CON 11 and pH 11 meter. Major ion chemistry (anions and cations) was measured using Ion Chromatograph (Dionex-500). For cationic analysis, 25  $\mu$ l of the filtered and acidified sample was introduced into a cation exchange column (CS 12A), where the ions were separated based on their charge-to-size ratio and were quantified using conductivity detector (ED 40). For anionic determination, 25  $\mu$ l of the filtered and non acidified sample was introduced into an anion exchange column (AS 11) and measured.

Stable isotopes ( $^2H$  and  $^{18}O$ ) were analysed using an isotope ratio mass spectrometer (GEO 20-20, Europa) by gas equilibration method. For  $\delta^2H$  analysis, 1 ml of the water sample was equilibrated with  $H_2$  along with Pt catalyst at  $50^{\circ}C$  for 1 h and the gas was introduced into the mass spectrometer. The  $\delta^{18}O$  of the sample was measured by equilibrating 1 ml of water with  $CO_2$  gas at  $50^{\circ}C$  for

**Table 1.** Hydrochemical and environmental isotope data of spring discharge and precipitation collected during September 2004 from Gaucher area

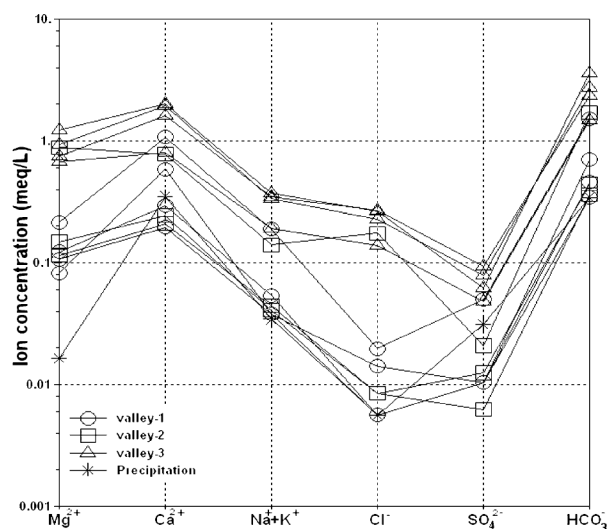
Sample ID	Altitude (m amsl)	Location	Temperature (°C)	pH	EC (µS/cm)	mg/l										Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	Na <sup>+</sup>	HCO <sub>3</sub> <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	δ <sup>2</sup> H (‰)	δ <sup>18</sup> O (‰)	3H (TU)
						F <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>											
V1SP1	1330		20.2	7.3	24	0.06	0.5	0.5	0	43	0.7	0.3	1	11.8	-53.2	-7.5									
V1SP2	1190		19.4	7	32	0.05	0.2	0.5	0	21	0.7	0.3	1.3	3.9	-51.4	-7.3									
V1SP3	1180	Chauki	19.7	7	34	0.06	0.2	0.5	0	28	1	0.4	1.5	5.9	-50.4	-7.3									
V1SP4	850	Jakhed	22.6	7.2	145	0.08	0.7	2.4	0	93	3.1	2.1	2.6	21.6	-57.9	-7.7									
V2SP1	1300	Sirpami	19.4	7.6	37	0.07	0.3	0.3	0	22	0.9	0.2	1.4	4.2	-52.5	-7.7									
V2SP2	1100		18.3	7.5	39	0.04	0.3	0.6	0	27	0.7	0.4	1.8	4.9	-50.3	-7.4									
V2SP3	1025	Gagotu	23.4	6.8	171	0.16	6.2	1	1.4	104	2.8	0.7	10.7	15.6	-54.5	-7									
V3SP0	1000	HESCO	21.2	7.2	272	0.24	8.1	3.8	11.3	167	5.7	3.4	11.4	38.8	-55.2	-7.4									
V3SP1	975		22.2	6.8	254	0.2	9.6	4.5	3.7	144	6.5	2.5	9.1	32.2	-52.4	-7.6									
V3SP2	930		23.3	7.6	311	0.22	9.3	3	2	220	7.5	1.8	15	40.2	-53.2	-7.5									
V3SP3	910	Nagariso	22.1	7	145	0.12	4.9	2.3	3.1	90	3.9	0.9	8.2	16	-53.9	-7.1									
Precipitation				6.6	40	0.02	0.2	1.5	0	21	0.5	0.5	0.2	7											

V, Valley; SP, Spring.

**Table 2.** Isotope data of precipitation during September–December 2004 from Gaucher area

Sample ID	Altitude (m amsl)	Location	September 2004		December 2004	
			$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)
RW 1	800	Gaucher	−56.3	−8.2	−54.0	−8.1
RW 2	990	Gwar	−65.8	−9.6	−63.5	−9.4
RW 3	1180	Chauki	−69.2	−10	−68.5	−10.3

RW, Rainwater.

**Figure 2.** Schoeller's plot of spring, river and rain water chemical data.

8 h and the equilibrated gas was introduced into the mass spectrometer. The measured values were reported as delta ( $\delta$ ) values<sup>31</sup>. The precision of measurement for  $\delta^2\text{H}$  was  $\pm 1\%$  and that for  $\delta^{18}\text{O}$  was  $\pm 0.1\%$ .

Tritium concentration in the water sample was measured using a liquid scintillation counter (Quantulus Model No. 1220 – Perkinelmer make) after electrolytic enrichment of the sample in tritium. 250 ml of the distilled water sample was electrolytically reduced to about 13 ml using mild-steel cathode and stainless steel-anode by passing regulated DC power at a temperature of about 2–4°C. 8 ml of the enriched sample after distillation was mixed with 12 ml of the liquid scintillation cocktail (Optiphase Hisafe 3, Perkinelmer make) in a 20 ml standard polyethylene counting vial<sup>32</sup> and counted for 500 min. The accuracy of the tritium measurement was 0.5 TU ( $1\sigma$ ).

## Results and discussion

Hydrochemical and environmental isotope results are given in Tables 1 and 2. In September 2004, the high-altitude springs in valleys 1 and 2 had temperature of about 19.5°C and electrical conductivities ranging from 25 to 40  $\mu\text{S}/\text{cm}$ , whereas low-altitude springs and valley-3

springs had temperatures of about 22–23°C and electrical conductivities of 145–310  $\mu\text{S}/\text{cm}$ . All spring waters had pH values in the range 6.6–7.6.

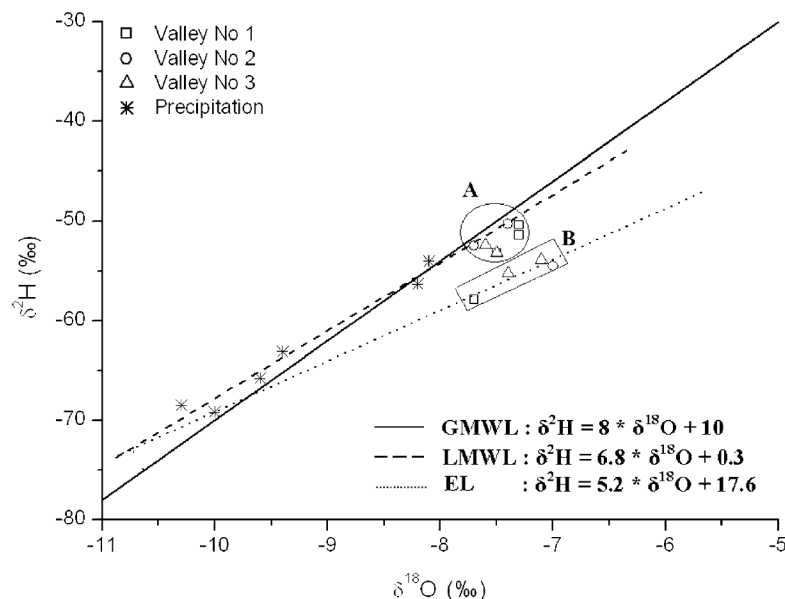
Hydrochemical data show that  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  were the dominant chemical species in spring waters and they are in the range 4–40, 1–15 and 20–220 mg/l respectively. The concentrations of other chemical species like  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ ,  $\text{Na}^+$  and  $\text{K}^+$  were low. The hydrochemical patterns of the various spring waters were studied using Schoeller's plot (Figure 2). All the spring waters belonged to Ca–Mg– $\text{HCO}_3$ -type. The high-altitude springs were less mineralized compared to the low-altitude springs. High-altitude springs of valleys 1 and 2 had similar chemical characteristics, whereas low-altitude springs of valleys 1 and 2 and all the springs of valley-3 had different patterns. This indicates that the chemistry of high-altitude springs was not influenced by water–rock interactions, whereas the chemistry of the low-altitude springs was modified by interaction with the formation. Low-altitude springs in valley-1 (e.g. V1SP4) showed less mineralization compared to other low-altitude springs. This could be mainly due to fast flow through fractures. The main sources of  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  were phyllite and mica schist.

Stable isotope data of precipitation collected from three different heights of the valleys, viz. 1180, 990 and 800 m amsl, during September 2004 show that  $\delta^{18}\text{O}$  varied from −10.0 to −8.2‰ and  $\delta^2\text{H}$  varied from −69.2 to −56.3‰. The isotopic composition of spring water varied from −7.7 to −7.0‰ for  $\delta^{18}\text{O}$  and from −57.9 to −50.3‰ for  $\delta^2\text{H}$ . The relationship between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in precipitation and spring samples is shown in Figure 3. It is observed that most of the isotopic values of the precipitation samples do not fall on the GMWL. The best-fit line for the precipitation samples was plotted to construct the LMWL. The equation for LMWL is given by:

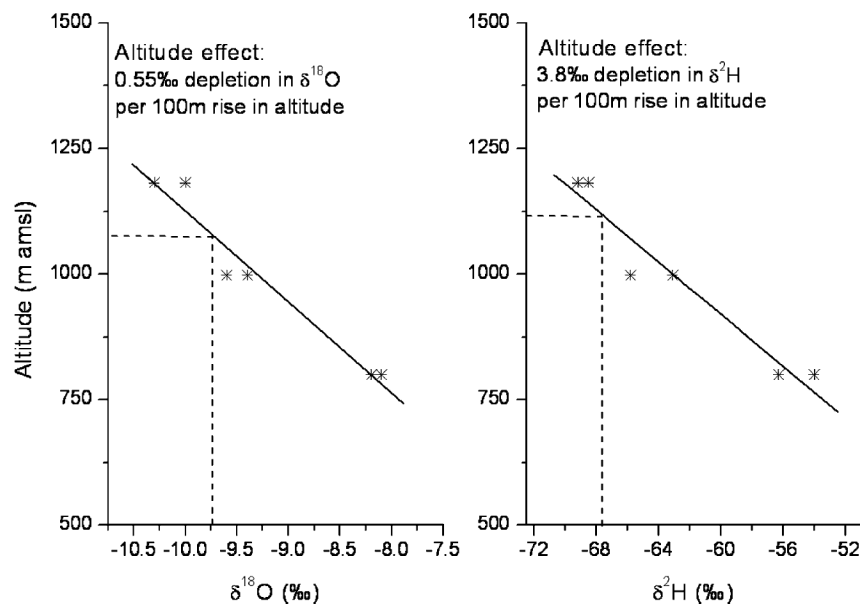
$$\delta^2\text{H} = 6.8 \times \delta^{18}\text{O} + 0.3 \quad (r^2 = 0.98, n = 6). \quad (2)$$

Compared to GMWL, LMWL has lower slope and y-intercept showing evaporation effect. This is because during precipitation, the raindrops might have undergone evaporation. Gat and Carmi<sup>33</sup> attributed the low y-intercept as a result of evaporation of precipitation occurring into dry air.

The spring waters fall in two clusters, viz. Group A and Group B in the  $\delta^{18}\text{O}$ – $\delta^2\text{H}$  diagram (Figure 3). Group



**Figure 3.** Relationship between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in precipitation and spring samples of Gaucher area.



**Figure 4.**  $\delta^{18}\text{O}$  vs altitude of rainwater samples from Gaucher area. Dotted line indicates recharge altitudes of low-altitude springs.

A comprises of samples from high-altitude springs and falls on the LMWL, indicating recharge by precipitation prior to evaporation. Group B belongs to the low-altitude springs and falls below the LMWL with a slope of 5.2, indicating evaporation effect. The equation of the evaporation line (EL) is given by:

$$\delta^2\text{H} = 5.2 \times \delta^{18}\text{O} - 17.6 \quad (r^2 = 0.93, n = 4). \quad (3)$$

For estimating the altitude effect, the stable isotopic compositions of the precipitation samples were plotted against their corresponding altitudes (Figure 4). The altitude effect was calculated as the inverse of the slope of the best-fit line. It was found to be  $-0.55\text{‰}$  for  $\delta^{18}\text{O}$  and  $-3.8\text{‰}$  for  $\delta^2\text{H}$  per 100 m rise in altitude.

Generally, the discharge rates of springs ranged from 0.7 to 120 l/min during the monsoon season, which re-

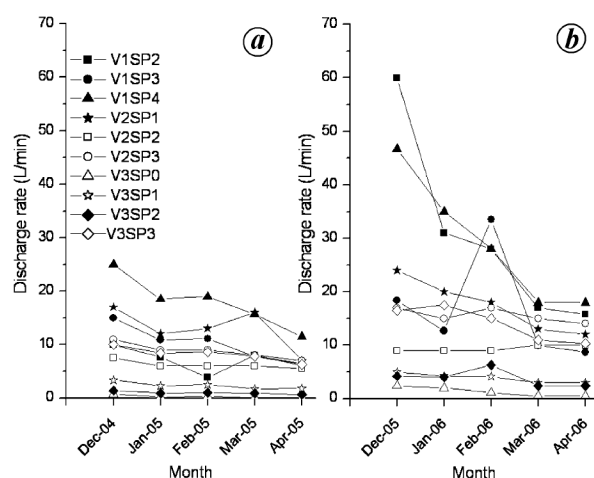


**Figure 5.** *a*, Subsurface dykes; *b*, New spring that appeared subsequently.

duced to 0.2–99 l/min within a month after the monsoon. The discharge measurements indicated that all the springs responded instantaneously to the precipitation events. During summer, most of the high-altitude springs dry up, whereas low-altitude springs continue to discharge with low rates. This shows that low-altitude spring discharges were a mixture of groundwater and precipitation, whereas only precipitation contributed to the high-altitude springs. This is further corroborated by hydrochemical data. The tritium content of the low-altitude springs was about 9.5 TU, whereas it was about 11.5 TU for high-altitude springs. This slight variation in tritium content can be attributed to relatively longer residence time of groundwater in low-altitude springs compared to that of high-altitude springs. The enrichment in isotopic composition of high-altitude springs compared to that of precipitation during September 2004 was due to the contribution from initial rains during July 2004. Hence recharge altitude for these springs could not be estimated. Since the values of the low-altitude springs fall on an EL, their isotopic composition before evaporation was calculated by extrapolating the EL to intersect the LMWL. The corrected isotopic composition of these springs was  $-10.7$  and  $-73\%$  for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  respectively. Using this corrected isotopic composition, the recharge area of the low-altitude springs was determined and it was found to be 1250 m amsl.

The topography and geology of the area suggests that the presence of thin, weathered, top soil cover underlain by hard and compact quartzite, phyllite and granite with a steep gradient does not allow the rainwater to percolate down, and hence the spring waters were mostly derived from seepage waters.

Based on geology, geomorphology, hydrochemistry and isotope information of the study area, the possible recharge zones to the springs in valleys 1, 2 and 3 were located at altitudes of 1270, 1330 and 1020 m amsl respectively.



**Figure 6.** Discharge rates of the springs (*a*) before and (*b*) after construction of recharge structures.

At these identified altitudes, water-conservation and artificial recharge structures like subsurface dykes (5 nos) in valley-1, check bunds (2 nos) in valley-2 and a few trenches in valley-3 were constructed for rainwater harvesting (Figure 5 *a*). Monthly spring discharge measurements were carried out during December 2004–April 2005 before the construction of the structures and also during the same period in the following year, after the construction. The cumulative discharge rate of ten springs was found to be increased from 375 to 708 l/min during the post-monsoon period and the data are given in Table 3. It was found that the discharge rates had not only increased considerably, but also were sustainable even during the dry period. Figure 6 shows discharge rates of springs before and after the construction of the recharge structures versus month of measurement. In addition

**Table 3.** Discharge rates of springs located in valleys 1, 2 and 3 in Gaucher area

Month	Before construction of artificial recharge structures						After construction of artificial recharge structures					
	December 2004	January 2005	February 2005	March 2005	April 2005	Cumulative discharge	December 2005	January 2006	February 2006	March 2006	April 2006	Cumulative discharge
Spring	l/min						l/min					
V1SP2	10	7.6	3.9	8	6	35.5	60	31	28	17	15.8	151.8
V1SP3	15	10.9	11.1	7.8	6.5	51.3	18.4	12.7	33.5	9.9	8.7	83.2
V1SP4	25	18.5	19	15.7	11.5	89.7	46.7	35	28	18	18	145.7
V2SP1	17	12	13	16	7	65	24	20	18	13	12	87
V2SP2	7.5	6	6	6	5.5	31	9	9	9	10	10	47
V2SP3	11	9	9	8	7	44	17	15	17	15	14	78
V3SP0	0.7	0.2	0.3	0.1	0.1	1.4	2.4	2	1.1	0.5	0.5	6.5
V3SP1	3.3	2.3	2.5	1.7	1.8	11.6	5	4.2	4.1	3	3	19.3
V3SP2	1.4	0.9	1	0.9	0.6	4.8	4.2	4	6.3	2.4	2.4	19.3
V3SP3	10	8.4	8.6	7.8	6.3	41.1	16.5	17.5	15	11	10.3	70.3
Cumulative discharge	375.4						708.1					

New spring discharge rate: 67 l/min.

to the existing springs, two new springs also appeared close to the subsurface dykes (Figure 5b). The cumulative discharge rate of these new springs was about 67 l/min. The significant increase in the spring discharge rates, their longer duration and formation of new springs can be attributed to proper identification of recharge areas and implementation of artificial recharge structures.

## Conclusion

From the present study, it can be concluded that the existing springs in the investigated area were seasonal and the spring discharges were mostly seepage waters flowing through the shallow weathered and fractured zone. The source of recharge to these springs was local precipitation and it was modern. The chemistry of high-altitude springs was similar to that of local precipitation, whereas water-rock interactions contributed to increased mineralization in low-altitude springs. It was observed that low-altitude spring discharges were a mixture of groundwater and local precipitation, whereas only precipitation contributed to the high-altitude springs. From the stable isotope variation in precipitation, altitude effect for the Himalayan region was estimated and it was found to be  $-0.55\%$  for  $\delta^{18}\text{O}$  and  $-3.8\%$  for  $\delta^2\text{H}$  per 100 m increase in altitude. Altitude effect was used to estimate the recharge areas of the low-altitude springs. Based on the local geology, geomorphology, hydrochemistry and isotope information, the possible recharge areas for valleys 1, 2 and 3 were identified and they are located at altitudes of 1250, 1330 and 1020 m amsl respectively. The recharge structures such as subsurface dykes, check bunds and contour trenches were constructed at the identified recharge areas in the three valleys for controlling subsurface flow and rainwater harvesting. During and after the following monsoon, it was observed that the discharge rates of the

springs had increased considerably and that they had not dried up in the following summer. This study demonstrates the application of isotope techniques to identify recharge areas of springs for rainwater harvesting in Gaucher area. Similar studies in other parts of the Himalayan region in Uttarakhand have been planned.

1. Todd, D. K., *Ground Water Hydrology*, John Wiley, New York, 1959, p. 321.
2. Clark, I. and Fritz, P., *Environmental Isotopes in Hydrogeology*, Lewis Publ., Boca Raton, 1997, p. 328.
3. Kendall, C. and McDonnell, J. J., *Isotope Tracers in Catchment Hydrology*, Elsevier Science, The Netherlands, 1998, p. 840.
4. Rao, S. M., Injected radiotracer techniques in hydrology. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1984, **99**, 319–335.
5. Tirumalesh, K., Shivanna, K., Noble, J., Narayan, K. K. and Xavier, K. T., Nuclear techniques to investigate source, origin of groundwater pollutants and their flow path at the Indian Rare Earths Ltd, Cochin, Kerala. *J. Radioanal. Nucl. Chem.*, 2007, **274**, 307–313.
6. Rangarajan, R. and Athavale, R. N., Annual replenishable groundwater potential of India – An estimate based on injected tritium studies. *J. Hydrol.*, 2000, **234**, 38–53.
7. Kulkarni, U. P., Radiotracer experiment to identify the location of seepage areas in the Borda minor irrigation tank, Yeotmal district, Maharashtra. In *Proceedings of the Nuclear and Radiochemistry Symposium*, Visakhapatnam, 1992, pp. 311–313.
8. Sukhija, B. S., Reddy, D. V., Nagabhushanam, P., Hussain, S., Giri, V. Y. and Patil, D. J., Environmental and injected tracers methodology to estimate direct precipitation recharge to a confined aquifer. *J. Hydrol.*, 1996, **177**, 77–97.
9. Shivanna, K., Kulkarni, U. P., Joseph, T. B. and Navada, S. V., Contribution of storms to groundwater recharge in the semi-arid region of Karnataka, India. *Hydrol. Process.*, 2004, **18**, 473–485.
10. Nair, A. R., Pendharkar, A. S., Navada, S. V. and Rao, S. M., Groundwater recharge studies in Maharashtra, Development of isotope techniques and field experience. In *Proceedings of the International Conference on Isotope Hydrology*, IAEA, Vienna, 1979, pp. 803–806.
11. Rao, S. M. and Kulkarni, K. M., Isotope hydrology studies on water resources in western Rajasthan. *Curr. Sci.*, 1997, **72**, 55–61.



12. Navada, S. V., Nair, A. R., Rao, S. M., Paliwall, B. L. and Doshi, C. S., Groundwater recharge studies in arid region of Jalore, Rajasthan using isotope techniques. *J. Arid Environ.*, 1993, **24**, 125–133.
13. Sukhija, B. S., Reddy, D. V. and Nagabhushanam, Isotopic fingerprint of palaeoclimates during the last 30,000 years in deep confined groundwaters of Southern India. *Quat. Res.*, 1998, **50**, 252–260.
14. Agarwal, M., Gupta, S. K., Deshpande, R. D. and Yadava, M. G., Helium, radon and radiocarbon studies on a regional aquifer system of the North Gujarat–Cambay region, India. *Chem. Geol.*, 2006, **228**, 209–232.
15. Navada, S. V. and Rao, S. M., Study of Ganga River–groundwater interaction using environmental oxygen-18. *Isotopenpraxis*, 1991, **27**, 382–384.
16. Jain, S. K., Navada, S. V., Nair, A. R. and Shivanna, K., Isotopic study on seawater intrusion and interrelations between water bodies: Some field examples. In *Isotope Techniques in Water Resources Development*, IAEA, Vienna, 1987, pp. 403–421.
17. Shivanna, K., Sinha, U. K., Joseph, T. B., Sharma, S. and Navada, S. V., Isotope hydrological investigation in arsenic infested areas of West Bengal, India. In Proceedings of the International Conference on Integrated Water Resources Management for Sustainable Development, New Delhi, 19–21 December 2000, pp. 490–500.
18. Tirumalesh, K., Shivanna, K. and Jalihal, A. A., Isotope hydrochemical approach to understand fluoride release into groundwaters of Ilkal area, Bagalkot District, Karnataka, India. *Hydrogeol. J.*, 2007, **15**, 589–598.
19. Shivanna, K., Navada, S. V., Nair, A. R. and Rao, S. M., Isotope and geochemical evidence of past seawater salinity in Midnapore groundwaters. In Proceedings of the International Conference on Isotope Techniques in the Study of Past and Current Environmental Changes in Hydrosphere and Atmosphere, IAEA, Vienna, 1993, pp. 199–212.
20. Craig, H., Isotopic variations in meteoric waters. *Science*, 1961, **133**, 1702–1703.
21. Fritz, P., Drimmie, R. J., Frape, S. K. and O'Shea, O., The isotopic composition of precipitation and groundwater in Canada. In Proceedings of the Symposium on Isotope Techniques in Water Resources Development, IAEA, Vienna, 1987, pp. 539–550.
22. Craig, H., Gordon, L. I. and Horibe, Y., Isotope exchange effects in the evaporation of water. 1. Low temperature experimental results. *J. Geophys. Res.*, 1963, **68**, 5079.
23. Dansgaard, W., Stable isotopes in precipitation. *Tellus*, 1964, **16**, p. 436.
24. Rozanski, K., Araguas-Araguas, L. and Gonfiantini, R., Isotope patterns in modern global precipitation. In *Continental Isotope Indicators of Climate*, American Geophysical Union Monograph, 1993, vol. 78, pp. 1–36.
25. Yonge, J. C., Goldenberg, L. and Krouse, H. R., An isotope study of water bodies along a traverse of southwestern Canada. *J. Hydrol.*, 1989, **106**, 245–255.
26. Yurtsever, Y. and Gat, J. R., Atmospheric waters. In *Stable Isotope Hydrology, Deuterium and Oxygen-18 in the Water Cycle*, Technical Reports Series No. 210, IAEA, Vienna, 1981, pp. 103–142.
27. Eriksson, E., Stable isotopes and tritium in precipitation. In *Guidebook on Nuclear Techniques in Hydrology*, Technical Reports Series No. 91, IAEA, Vienna, 1983, pp. 19–33.
28. Clark, I. D., Fritz, P., Michel, F. A. and Souther, J. G., Isotope hydrogeology and geothermometry of the Mount Meager geothermal area. *Can. J. Earth Sci.*, 1982, **19**, 1454–1473.
29. Bortolami, G. C., Ricci, B., Susella, G. F. and Zuppi, G. M., Isotope hydrology of the Val Corsaglia, Maritime Alps, Piedmont, Italy. In Proceedings of the IAEA Symposium on Isotope Hydrology, Neuherberg, Germany, 1979, vol. I, pp. 327–350.
30. Srivastava, R. N. and Ahmad, A., *Geology and Structure of Alaknanda Valley*, Garhwal Himalaya, Geological Survey of India, 1977, pp. 225–251.
31. Coplen, T. B., New guidelines for reporting stable hydrogen, carbon and oxygen isotope-ratio data. *Geochim. Cosmochim. Acta*, 1996, **60**, 3359–3360.
32. Nair, A. R., Possibilities of liquid scintillation counting for tritium and radiocarbon measurements in natural water. In Proceedings of the Workshop on Isotope Hydrology, Bhabha Atomic Research Centre, Mumbai, 1983, pp. 41–56.
33. Gat, J. R. and Carmi, I., Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. *J. Geophys. Res.*, 1970, **75**, 3039–3048.

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