Report No.: NIH/TR/2023-24
Final Report

STUDIES ON WATER SOURCE AND HYDROLOGICAL BEHAVIOUR OF THE TWO SMALL LAKES AT SRI BADRINATH, DISTRICT CHAMOLI, UTTARAKHAND

Submitted to

Uttarakhand State Disaster Management Authority (USDMA)
Government of Uttarakhand

By

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आपो हि ष्ठा मयोभुवः

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Deptt. of WR, RD & GR,
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Jal Vigyan Bhawan, Roorkee-247 667 (Uttarakhand), INDIA

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November, 2023

Director: **Dr. Sudhir Kumar**

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1.0 GENERAL

Lakes are important components of the hydrologic cycle and are valuable sources of fresh water. They serve variety of purposes and thereby act as catalysts in the development of a region. However, this popularity of theirs often becomes the cause of their deterioration resulting into qualitative and quantitative degradation. The situation is further aggravated with problems such as sedimentation or eutrophication which could be natural or manmade or both. As such, management of lake waters both in terms of quantity and quality is of great significance. Sincere efforts are now being made at various levels to conserve the lake water resources for the socio-economic benefit of the society.

The various processes occurring in any lake ecosystem are directly or/and indirectly interrelated with the various hydrological processes. Hence, it is essential to understand the various hydrological processes of the lake ecosystem, so that systematic and scientific conservation and management measures can be suggested and taken up for the lake. Integrated hydrological investigations are hence significant and essential for any lake.

A request has been received by the National Institute of Hydrology, Roorkee from Hon. Secretary, Government of Uttarakhand vide DO No. 45 dated 28th April, 2022 for carrying out hydrological studies on the two small lakes located in the holy town of Sri Badrinath in Uttarakhand. The present study has been carried out in response to this request.

2.0 OBJECTIVES

Keeping in the view the request of the Government of Uttarakhand, objectives of the study are:

i) To assess the water sources of the lakes, and

ii) To understand the hydrological behaviour of the lakes

3.0 STUDY AREA

The study has been carried out on two high altitude Himalayan lakes located in the holy town of Sri Badrinath in Chamoli district of Uttarakhand state. The Badrinath town is situated in the cold climatic condition of Garhwal hills, near the banks of the Alaknanda River at an elevation of about 3100 meters amsl. The town lies between the Nar and Narayana mountain ranges and in the shadow of Nilkantha peak. It is covered by snow during significant period of the year. ***Figure 1*** presents the satellite view of the lakes while ***Figure 2*** provides the view under ice covered conditions.

Both the lakes are small and shallow. The lakes are likely to receive glacial melt water besides runoff from the surrounding areas, and groundwater contribution. These lakes are likely to be subjected to anthropogenic pressure by both local residents and in particular, the large number of tourists in the town. Since the lakes are located in the Himalayas, they are also likely to be subjected to sedimentation. Further some renovation and beautification work has been carried out for the lakes in recent times. However, no systematic scientific investigations on the various hydrological processes and hydrological behaviour of the lakes have been reported for the two lakes. The present study has undertaken these investigations.

Figure 1: A satellite view of the two lakes in Badrinath

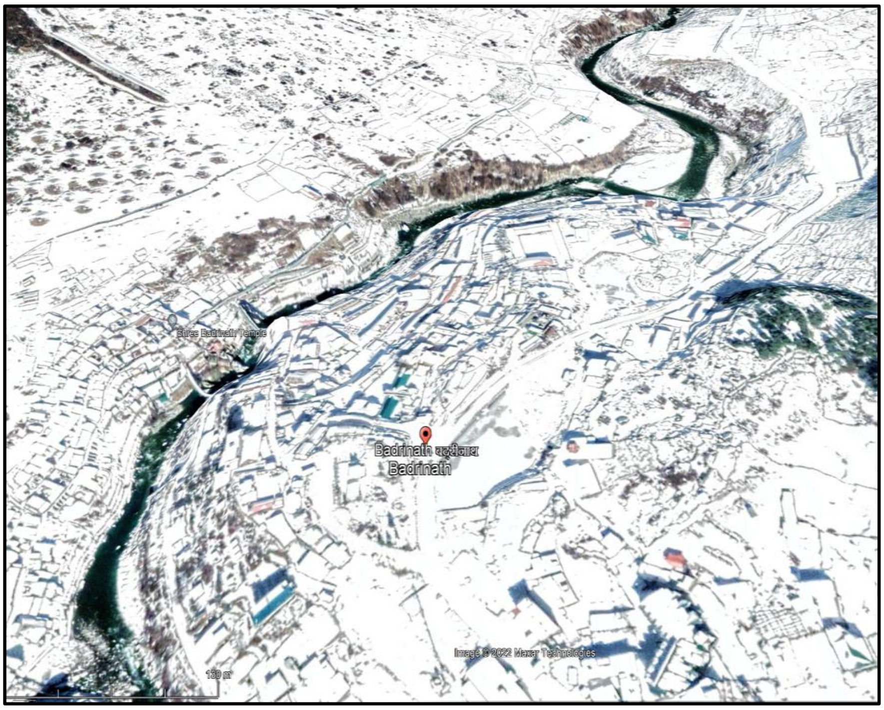

Figure 2: A satellite view of lakes under ice covered conditions

4.0 FILED INVESTIGATIONS

A total of five field visits have been made by the study team from NIH, Roorkee under the study during May 2022 to September 2023.

The first field visit was undertaken during 31-05-22 to 03-06-22. Following field works were carried out:

- Preliminary survey of study area
- Collection of water samples from different sources (Dhara, river, Tapt kund, lakes and snow) for isotopic and chemical analysis.
- Discussion with consultant related to lakes work.
- Discussion with PWD officers and selection of the location for installation of raingauge, water level recorder.

The second field visit to the study area was undertaken during 13-09-2022 to 15-09-2022. Following field works were carried out:

- Preliminary bathymetry survey of Shesh Netra and Badrish Lake.
- Collection of water samples from different sources (Dhara, river, Tapt kund, lakes and snow) for isotopic and chemical analysis.
- Installation of water level recorder at Shesh Netra Lake.

The third field visit was undertaken during 24-09-2022 to 28-09-2022. Following field works were carried out:

- Collection of water samples from different sources (Dhara, river, Tapt kund, lakes and snow) for isotopic and chemical analysis.

The fourth field visit was conducted during 12-06-23 to 15-06-23. During this field visit, following works were carried out:

- Collection of water samples from different sources (Dhara, river, Tapt kund, lakes and snow) for isotopic and chemical analysis.
- Bathymetry survey of Shesh Netra and Badrish Lake
- Installation of water level recorder at Badrish Lake and ORG at PWD office
- Engaging a person for water sample collection from river, lake, Tapt kund, dhara, snow and rain water in weakly basis.

The fifth field visit was undertaken during 25-09-23 to 27-09-23. During this field visit, following works were carried out:

- Collection of water samples from different sources (Dhara, river, Tapt kund, lakes and snow) for isotopic and chemical analysis.
- Uninstallation of water level recorder at Badrish lake

As mentioned above, a data observer has been appointed to collect the samples from various sources including rain and snow, for isotope analysis. He is also recording the rainfall data from the ORG installed under the study at the PWD office. The data and samples have been collected for the period from June 2023 to September 2023.

Figure 3 presents some photographs of different field works carried out during different field visits.

Figure 3: Some photographs of different field works carried out during June 2022, September 2022 and June 2023

5.0 BATHYMETRY OF LAKES

Bathymetric data are of fundamental importance in hydrological studies of lakes, as basic morphometric parameters such as length of the lake, width of the lake, surface area of the lake, volume of the lake etc are determined based on the bathymetry of the lake. As a matter of fact, bathymetric data are the starting points for many scientific investigations on lakes. Water balance study requires the knowledge of storage capacity and volumes of lakes. As such, the estimation of the depth-area-capacity relationships is the fundamental requirement of these studies. The surface areas and volumes of the lake at different lake water levels are determined from the depth-area-capacity curve which is derived from the bathymetric data. Long term bathymetric data are used to determine the sedimentation rate of the lake.

Bathymetric surveys of the two lakes was initiated during September 2022 and completed during the field visit of June 2023. ***Table 1*** presents the morphometric parameters of Shesh Netra and Badrish lake as derived from the bathymetric analysis while ***Figure 4*** shows the spatial distribution of the depth of the Shesh Netra and Badrish lake along with depth contours. The maximum length and width of the Shesh Netra lake is 212.48 m and 66.00 m respectively while the maximum length and width of the Badrish lake is 77.04 m and 50.77 m respectively. The maximum depth of the Shesh Netra lake is 2.42 m while the mean depth comes out to be 1.81 m. The maximum depth of the Badrish lake is 2.57 m while its mean depth comes out to be 1.41 m. The maximum surface area and storage capacity of the Shesh Netra lake is observed to be 4676 m^2 and 8448 m^3 respectively. As far as Badrish lake is concerned, its maximum surface area and storage capacity is observed to be 3177 m^2 and 4493 m^3 respectively.

Table 1: Morphometric parameters of Badrinath lakes

Parameter	Shesh Netra Lake	Badrish Lake
Maximum Length (m)	212.48	77.04
Maximum Width (m)	66.00	50.77
Maximum Depth (m)	2.42	2.57
Mean Depth (m)	1.81	1.41
Surface Area (m^2)	4676	3177
Volume (m^3)	8448	4493

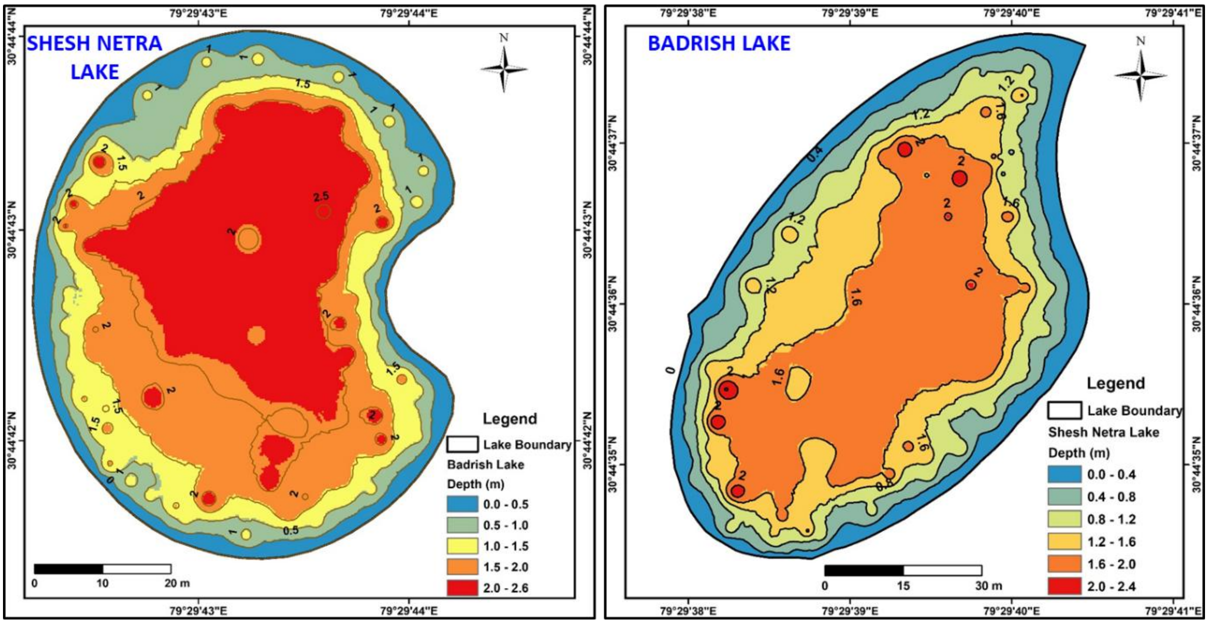

Figure 4: Depth of the lakes at various points along with depth contours

The depth versus area and depth versus volume curve of the Shesh Netra lake are shown in ***Figure 5*** and ***Figure 6*** respectively and while for Badrish lake, the depth versus area and depth versus volume curves are shown in ***Figure 7*** and ***Figure 8 respectively***. Table 2 shows surface area and volume of the both lake at different depths of the lake.

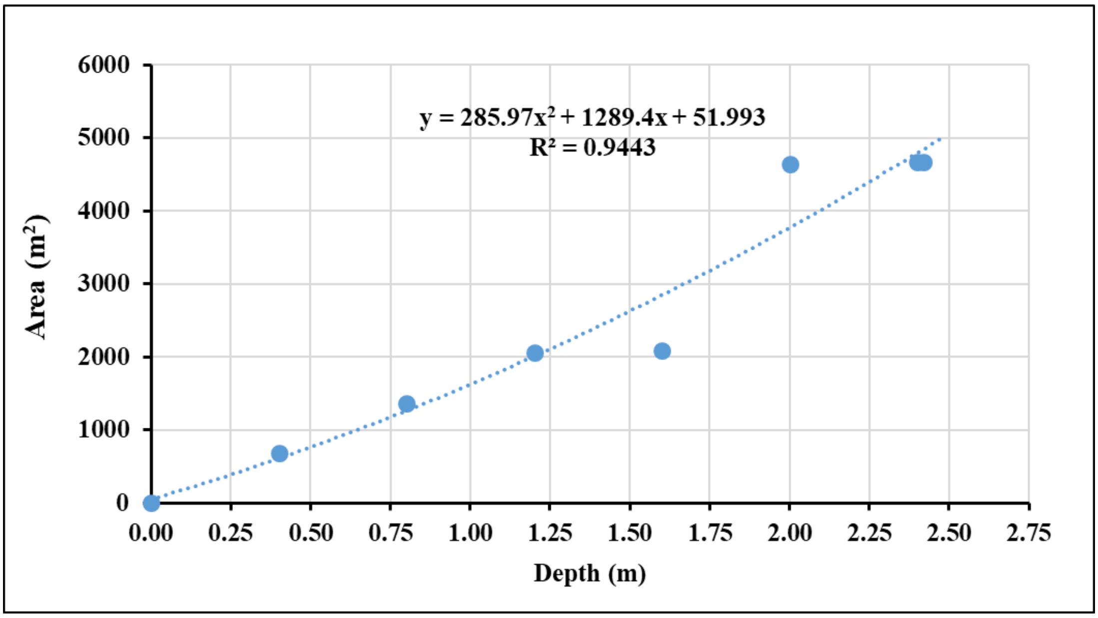

Figure 5: Depth versus surface area curve for Shesh Netra lake

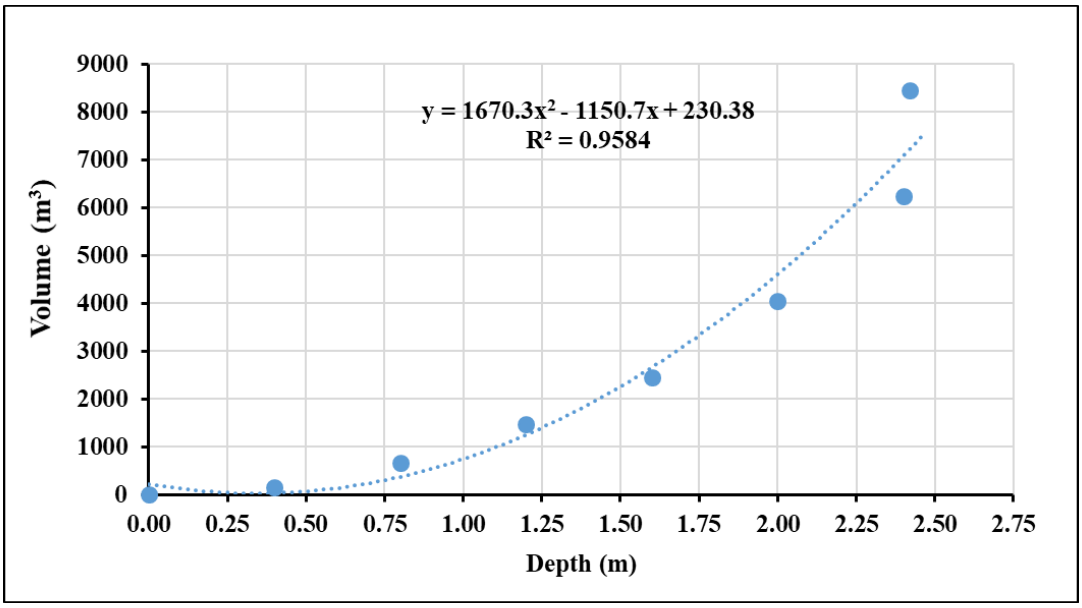

Figure 6: Depth versus volume curve for Shesh Netra lake

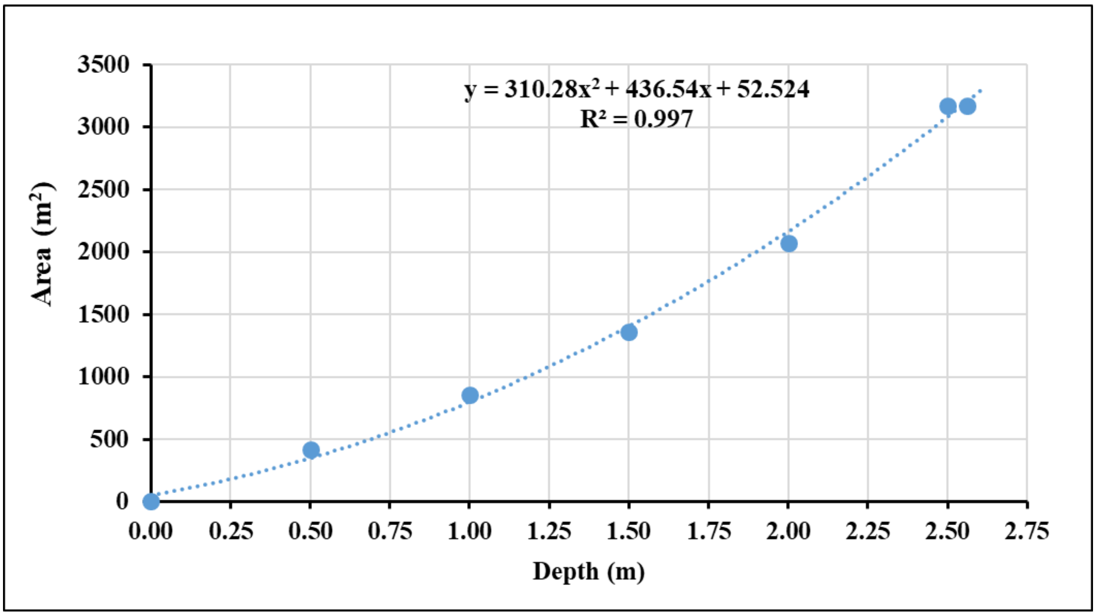

Figure 7: Depth versus surface area curve for Badrish lake

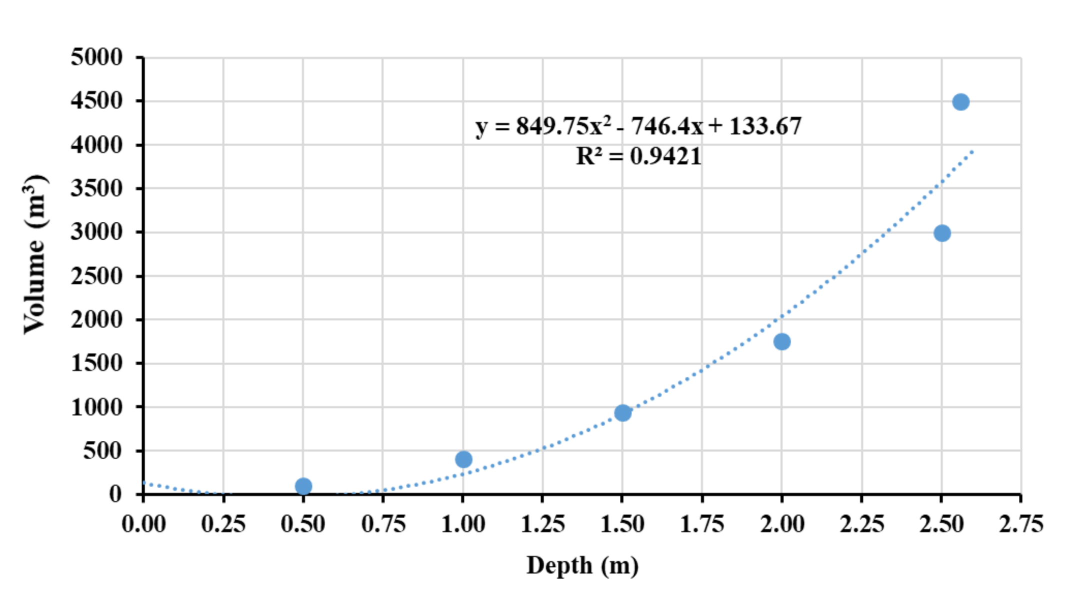

Figure 8: Depth versus volume curve for Badrish lake

Table 2: Surface area and volume of the lakes at different depths

Depth (m)	Shesh Netra Lake		Depth (m)	Badrish Lake	
	Area (m²)	Volume (m³)		Area (m²)	Volume (m³)
2.42	4675.66	84448	2.56	3176.46	4493
2.40	4675.46	6244	2.50	3173.82	2993
2.00	4645.04	4046	2.00	2075.11	1751
1.60	2083.83	2457	1.50	1362.88	935
1.20	2066.07	1474	1.00	855.77	406
0.80	1369.72	658	0.50	415.10	102
0.40	689.85	167	0	0	0
0.00	0.00	0			

6.0 HYDROLOGICAL BEHAVIOUR OF LAKES

Understanding the hydrological behaviour of the lakes is an essential requirement for efficient management of the lakes. For example, knowledge of the estimates of the water available in lakes, at different points of time, is required to plan the uses of the lake water for various demands, and may provide the basis for making alternate arrangement of water, for the periods for which water may be required in the lakes but may not be available. However, to understand the hydrological behaviour of the lake in totality one needs proper and complete understanding of the various hydrological aspects such as hydro-meteorology, evaporation, ground-water lake interaction, runoff from lake catchment, water level fluctuations in lakes etc.

Under the present study various data are being collected for the assessment of the water balance of the lake and thereby to understand the hydrological behaviour of the lake. The data include rainfall data for the study area and lake water levels.

6.1 Hydro-meteorological aspects

6.1.1 Rainfall characteristics

No historical observed rainfall data is available for Badrinath. So grid rainfall data (0.1^0 x 0.1^0) for Badrinath for 41 years for the period of 1982 to 2022 have been obtained from NASA Power Larc web site. The data are presented in ***Figure 9*.** As per this grid data, the average annual rainfall for Badrinath is observed to be 806.2 mm while the average annual monsoon rainfall is 620.5 mm ***Figure 10***. The average number of annual rainy days are 81 of which 60 occur during the monsoon months of June to September ***Figure 11***. No increasing or decreasing trend has been observed either in the annual rainfall or in monsoon rainfall for the study area of Badrinath. However, the annual number of rainy days show an increasing trend, as per the grid data.

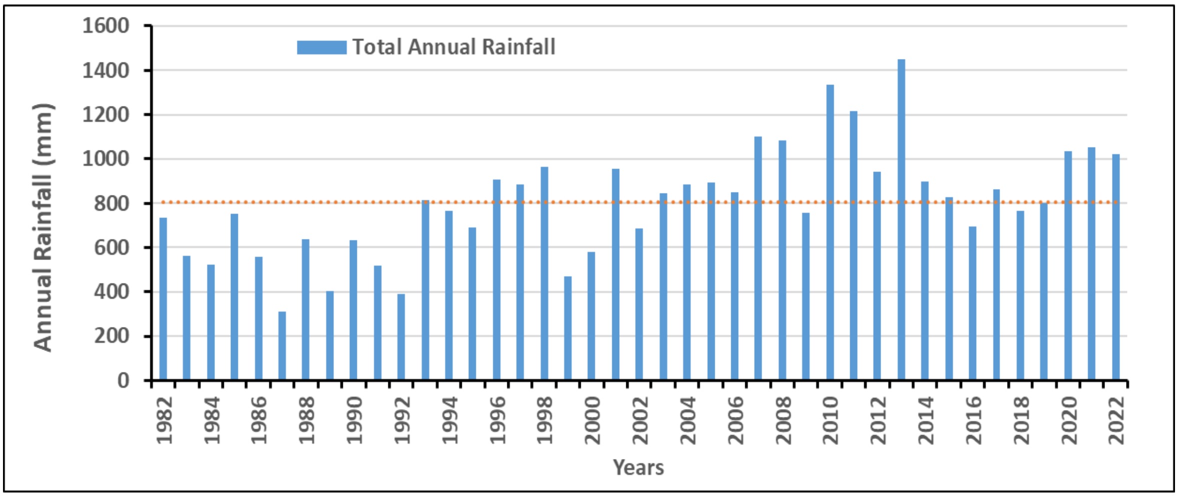

Figure 9: Annual rainfall at Badrinath as per grid data

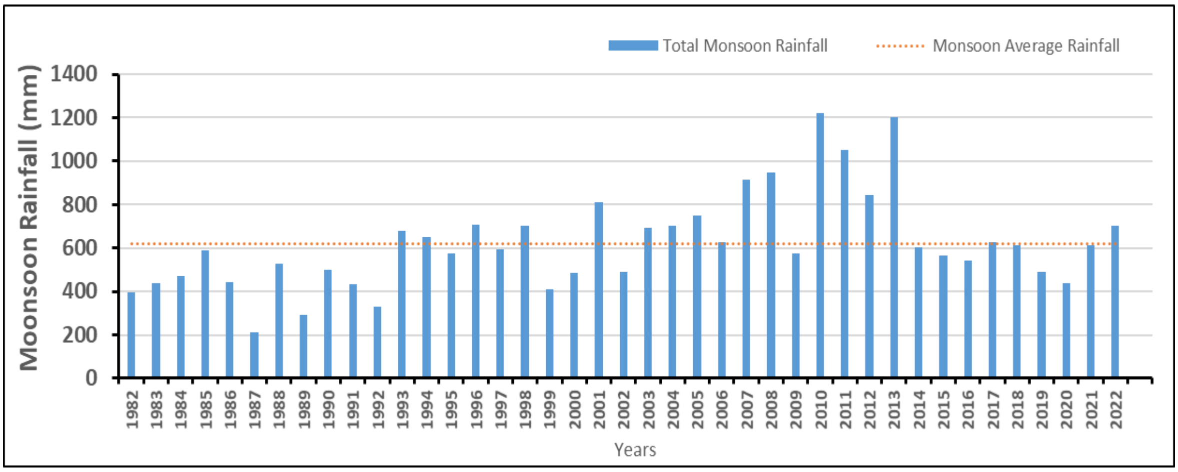

Figure 10: Monsoon rainfall at Badrinath as per grid data

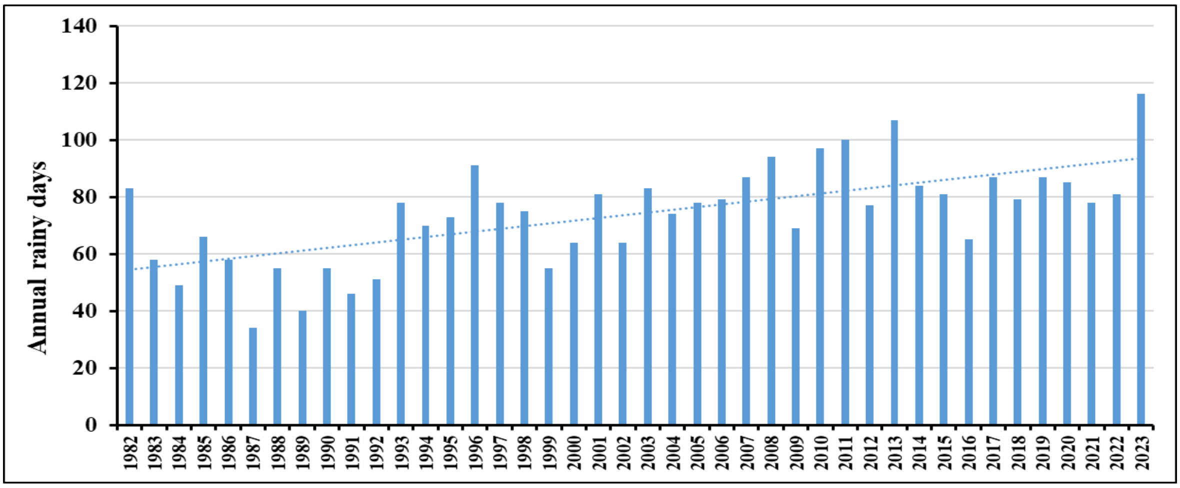

Figure 11: Annual rainy days at Badrinath as per grid data

Ordinary rain gauge has been installed in the study area to monitor rainfall as well as for collection of rainfall samples ***(Figure12)***.

Figure 12: Rain gauge installed at the PWD office in Badrinath

Figure 13 presents the data of rainfall of the study area for the period from 14 June to 26 September 2023, collected from the ORG installed in the study area The total rainfall observed during the period from 14 June to 26 September 2023 is 387.4 mm. The maximum one-day rainfall recorded at the study area during the study period was 36 mm which was recorded on 9 September 2023. A significant variation is seen in this data when compared to the grid data. It is for this reason that for the purpose of water balance and understanding the hydrological behaviour of the lake, on site data collected from the Raingauge installed in the study area has only been used in the present study, as it is an observed data.

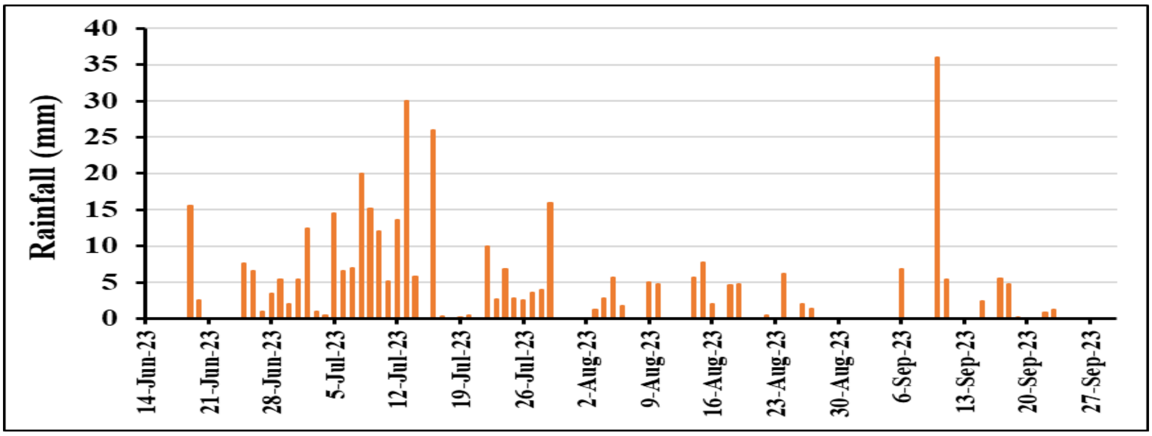

Figure 13: Observed rainfall data for the study area

6.1.2 Evaporation rates

No method exists for direct measurement of actual lake evaporation. It has to be determined indirectly. A number of methods and models have been developed to indirectly estimate evaporation from the lakes, such as energy balance models, water balance models, mass transfer models, combination models, pan evaporation models, and empirical models. However, many of these methods need extensive data which are not available for the study area. As far as present study is concerned unavailability of meteorological data on wind, relative humidity, radiation, dry bulb and wet bulb temperature and sunshine hours prohibits the use of any of the existing model of evaporation estimation for lakes. The only available meteorological data with the investigators is mean temperature which has been obtained from grid data. These data have been used in the present study to estimate lake evaporation. Based on the previous study carried out by NIH on Nainital lake, first a relationship has been developed for estimating lake evaporation from air temperature data. Keeping in view the variation in the relationship during different seasons, three different equations were developed for three different seasons. These are shown in ***Figure 14***. These equations were applied in the present study to get daily evaporation rates from daily temperatures during the various months in these seasons. The daily estimates were averaged to get mean rate of evaporation for different months. The average evaporation rates for the study area for different months are presented in ***Figure 15.***

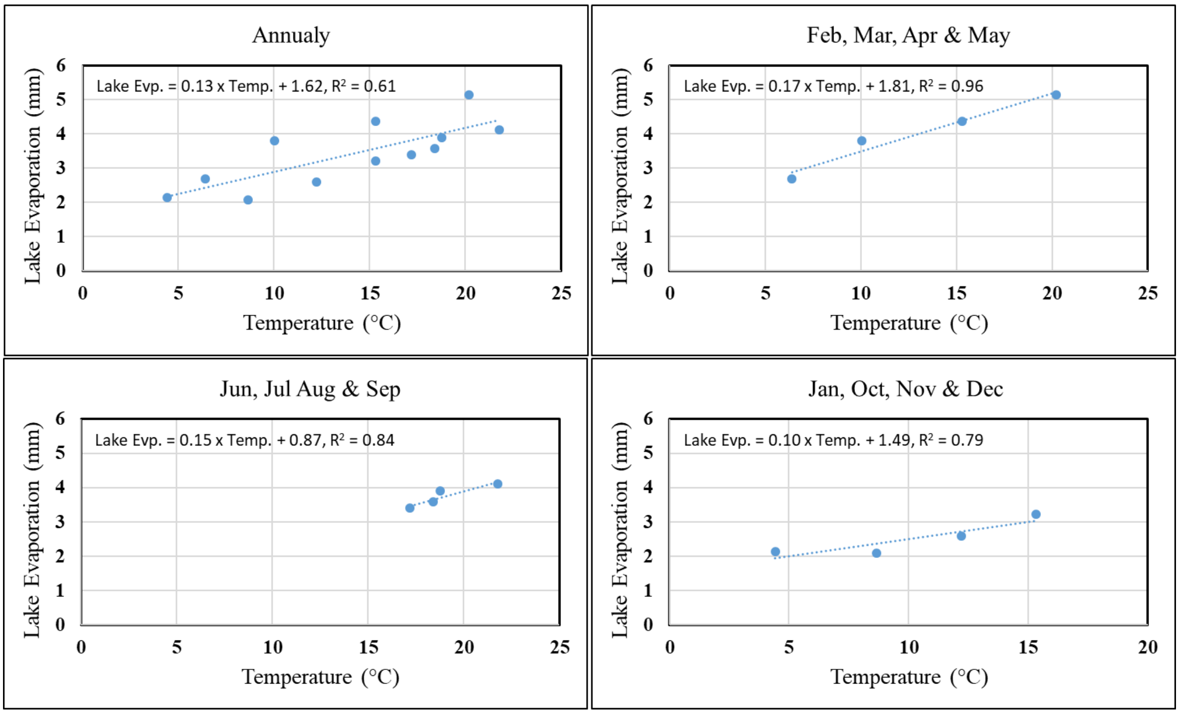

Figure 14 : Equations for estimating evaporation from Badrinath lakes for different seasons

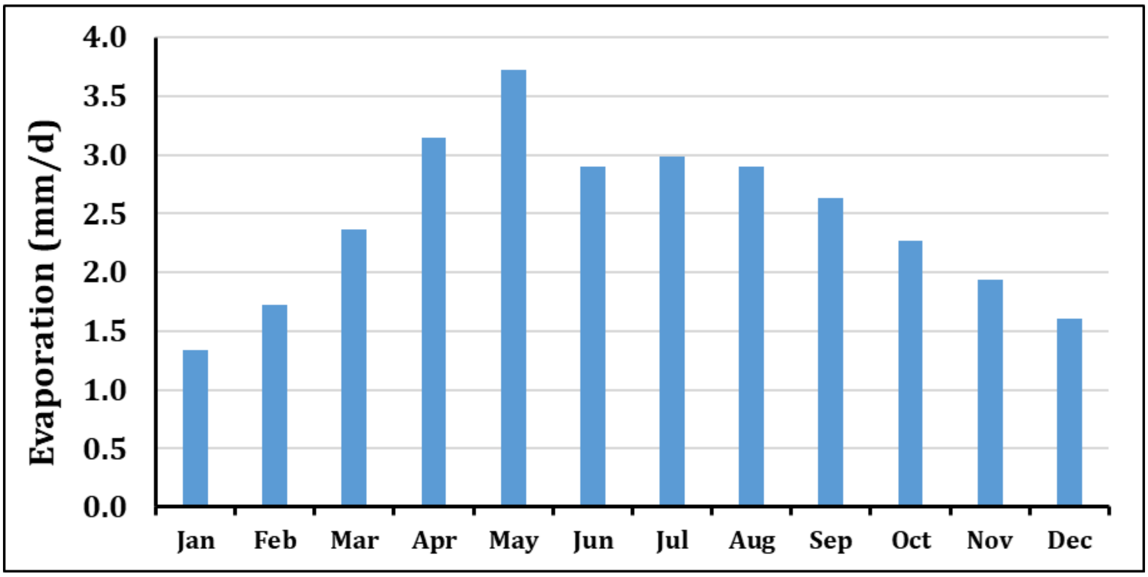

Figure 15: Average monthly evaporation rates for the Badrinath lakes

6.2 Water level variation

Lake water level variation is an indicator of the hydrological behaviour of the lake. As such, analysis of the lake water level variation is important for any lake to understand its hydrological behaviour. No historical lake water level data are available for the lakes of

Badrinath. Automatic water level recorder has, therefore, been installed in the lake for generation of lake water level data for the present study. The data have been collected for the period from June to September 2023.

The variation is lake water levels of the two lakes is discussed below.

6.2.1 Shesh Netra Lake

The variation of daily lake water level with rainfall for the Shesh Netra lake for the period of 17 September 2022 to 26 September 2023., is presented in ***Figures 16.*** The Shesh Netra lake water level varies in the range of 1.15 m to 2.13m. The lake level variation of ~0.98 m has been recorded for Shesh Netra lake during the period of 17 September 2022 to 26 September 2023.

The water level start raising from mid of September and reached the during first week of November. After this, it starts declining till third week of April, after which it again starts rising.

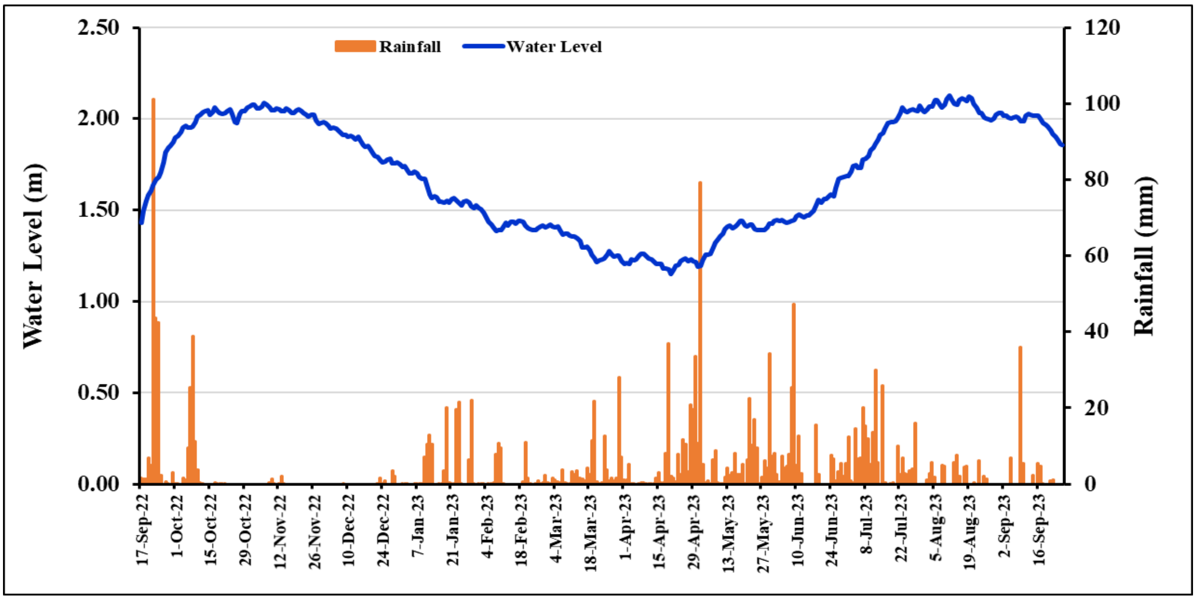

Figure 16: Variation of water level with respect to rainfall for Shesh Netra lake

6.2.2 Badrish Lake

The variation of daily lake water level with rainfall for the Badrish lake for the period of 16 June 2023 to 26 September 2023., is presented in ***Figures 17.*** The Badrish lake water level varies in the range of 1.24 m to 1.63 m. The lake level variation of ~0.39 m has been recorded for Badrish lake during the period of 16 June 2023 to 26 September 2023.

During the water level observation period, the water level started rising from July 2023 after which it did not vary much. The maximum water level was observed during September, 2023.

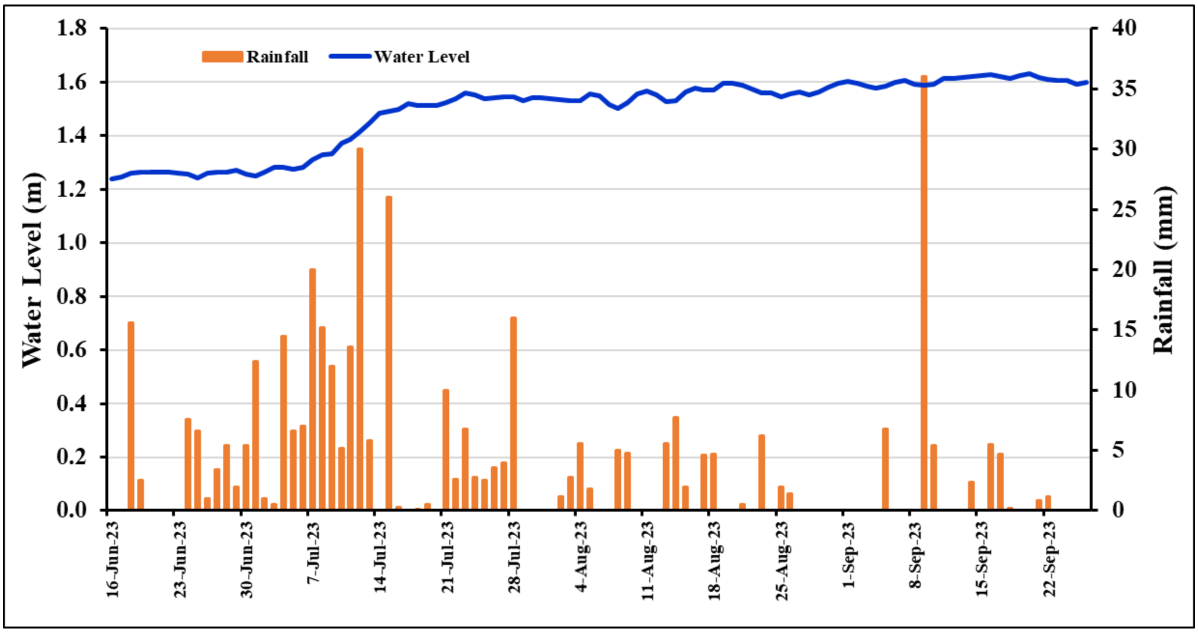

Figure 17: Variation of water level with respect to rainfall for Badrish lake

A comparison of water level variation of the two lakes is presented in ***Figure 18.*** Both the lakes appear to behave more or less similarly, as far as lake water level variation are concerned.

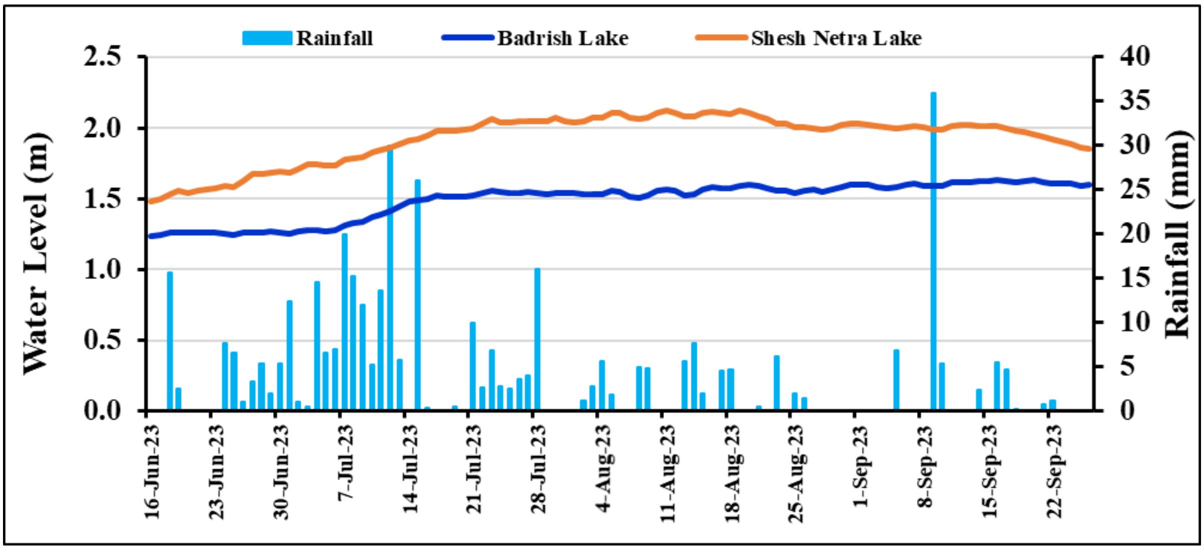

Figure 18: Comparison of water level variation in two Badrinath lakes during the same period

6.3 Water Balance of the Lakes

A simple water balance equation for any lake can be written as:

Inflow - Outflow = Change in lake storage

The above water balance equation is based on the natural law of conservation of mass. It is applicable not only for any lake, but for any natural system. It is briefly explained here for easy understanding:

Assume that a certain amount of water is coming into the lake and a certain amount of water is going out of the lake during the same time period. Then, because of in-coming of water to the lake, the water level in the lake will increase and, because of the going out of water from the lake, the water level will come down. If during some specific period, say a day or a week or a month or a season or a year, the amount of water coming to the lake is equal to the amount of water going out of the lake, the net result will be "no change" in the lake water level or lake water storage. If the quantity of incoming water is more than the quantity of water going out, then the net result will be a rise in the lake level, i.e. increase in storage of lake. Alternatively, if the quantity of water coming to the lake is less than the quantity of water going out of the lake, the lake water level will fall causing decrease in the lake water storage.

The water balance equation above involves three major terms: (i) Inflow to the lake, (ii) Outflow from the lake and (iii) Change in storage of lake. The major factors which contribute to the lake inflow are runoff water from the catchment coming through the inflowing stream and the water which is falling directly on the lake as rainfall. There may be a third component which is the water coming as groundwater inflow. The major factors which contribute to the outflow are outflow through sluice gates or overflows from the lake, water being lost through the processes of evaporation, water being pumped out of the lake, and seepage from the lake. The seepage could be through the sides or bottom of the lake as underground outflow or through the leakages in sluice gates.

In case of Shesh Netra lake and Badrish lake, the inflow term includes surface inflow from the catchment, subsurface inflow (groundwater inflow) and inflow contributed by the direct precipitation falling over the lake. The outflow terms include underground outflow from the lake and evaporation losses from the lake.

The water balance equation for Shesh Netra lake and Badrish lake, therefore, cab be written as:

$$\Delta S = (I_S+I_G+I_P)-(O_E+O_G)$$

Where,

ΔS	=	Change in lake storage during a period, MCM
I_S	=	Inflow due to surface runoff from rainfall in catchment, MCM
I_G	=	Inflow due to sub-surface (groundwater) flow, MCM
I_P	=	Inflow due to direct rainfall over the lake, MCM
O_E	=	Outflow due to evaporation from the lake
O_G	=	Outflow due to subsurface out flow, MCM

Due to availability of observed rainfall data only for the period from 19 June 2023 to 26 September 2023, the water balane has been carried out for this period only. Detailed water balance computations have been carried out on monthly basis for this period. The daily data have been converted into monthly data. Water balance has been carried out in volumetric m^3 units.

Estimation of different parameters of water balance needs detailed data of various hydro-meteorological parameters such as rainfall, evaporation, discharge, runoff from catchments, outflow through lakes, water levels, ground water levels in the lake catchment and the downstream, aquifer parameters etc. Direct measurements of evaporation are not done and it has to be estimated through various models such as energy balance models or Penman combination model for getting reliable estimates. Even these models need extensive climatic data which are not available with the investigators for the study area. Under such heavy constraints of data availability, precise estimation of different water balance components is almost an impossible task. However, best efforts have been made in the present study to reasonably estimate the water balance components with the available data, using alternate approaches and reasonable assumptions. The estimation of the various components of the lake water balance is discussed below.

6.3.1 In-flow due to rainfall falling directly over the lake

Rainfall falling directly over the lakes causes inflow to the lake. It is estimated from the lake surface area. The volume of water added to the lake due to rainfall falling directly over the lakes has been estimated for both the lake for the observation period. It is shown in ***Figure*** 19 for Shesh Netra lake and in figure for the Badrish lake. The maximum volume added to the Shesh Netra lake due to direct rainfall over it was 473.2 m^3 on 23.9.2023 while for the Badrish lake it was 114.4 on 10.9.2023.

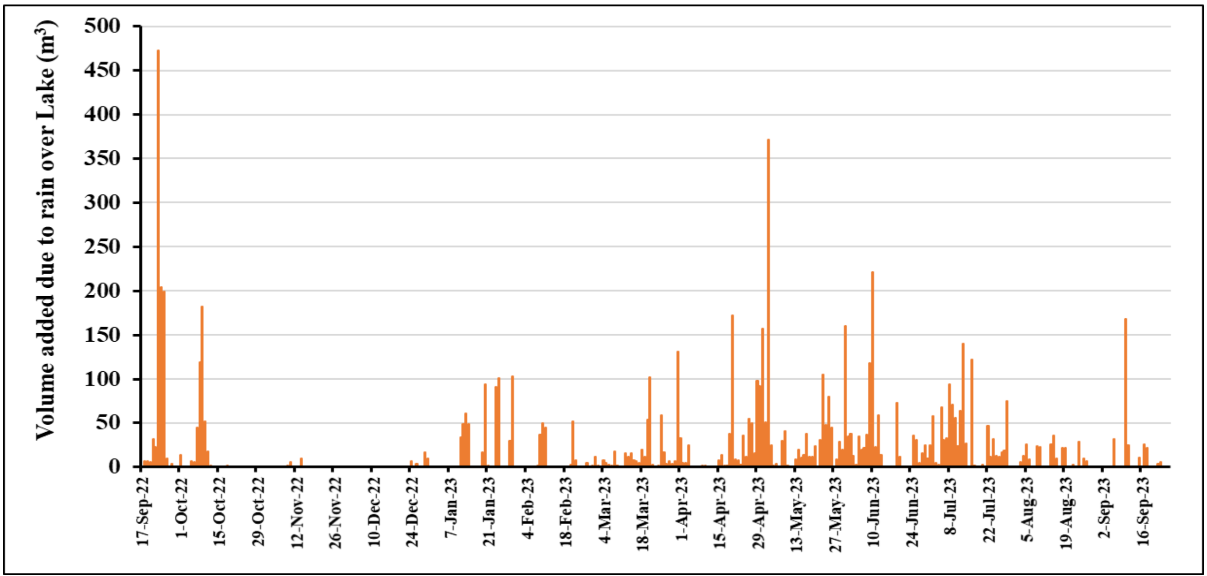

Figure 19: Volume of water added due to rain falling directly over Shesh Netra Lake

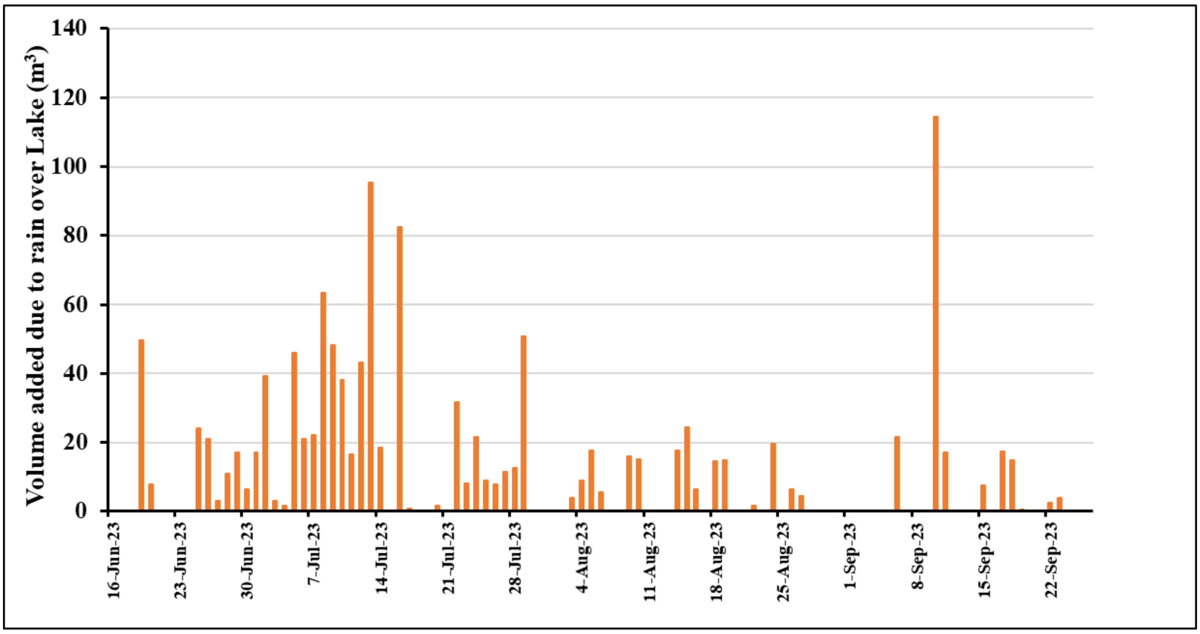

Figure 20: Volume of water added due to rain falling directly over Badrish Lake

6.3.2 In-flow due to Surface runoff

Surface runoff is the volume of water added by the rainfall falling over the catchment of the lakes and travelling to the lake. There is no stream in the lake catchments and runoff is mostly in the form of overland flow. So, it has been estimated using the runoff coefficient. Based on the literature, a runoff coefficient of 0.2 has been used for the lake catchments. Since the lake catchments are smaller in size, the runoff generated is not very significant. ***Figure 21 and Figure 22*** presents the estimated runoff for both the lakes respectively. The runoff is zero when there is no rainfall. The maximum runoff observed during the observation period was 557.1 m^3 for the Shesh Netra lake on 22.9.2022 and 84.2 m^3 for the Badrish lake on 9.9.2023.

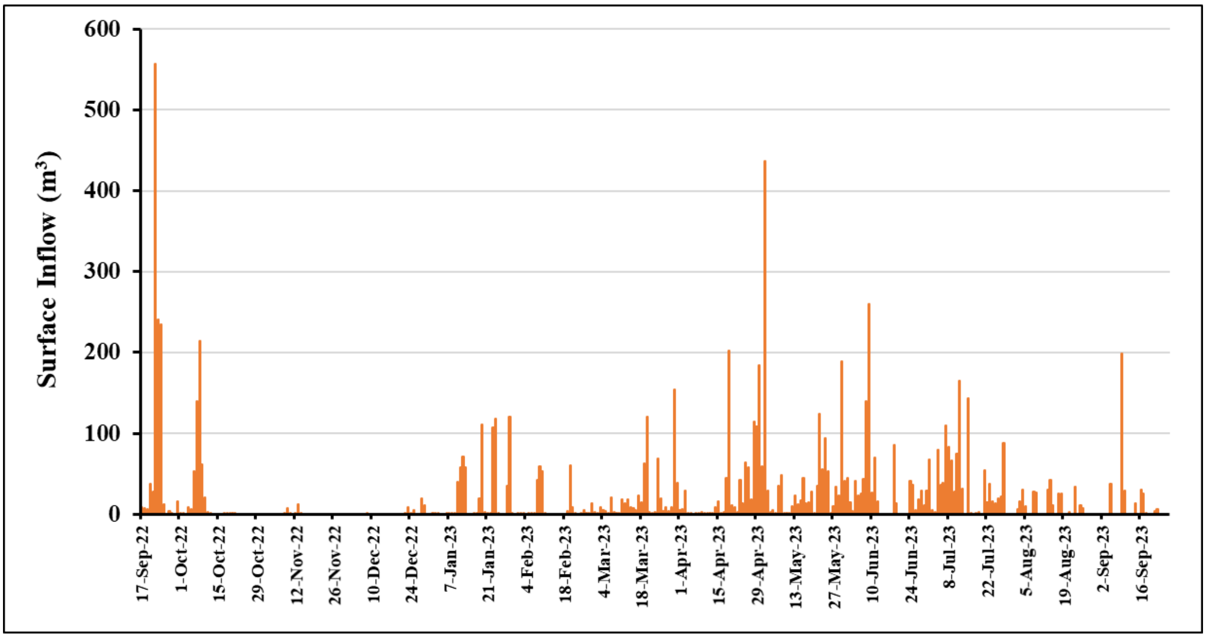

Figure 21: Estimated surface runoff for Shesh Netra Lake

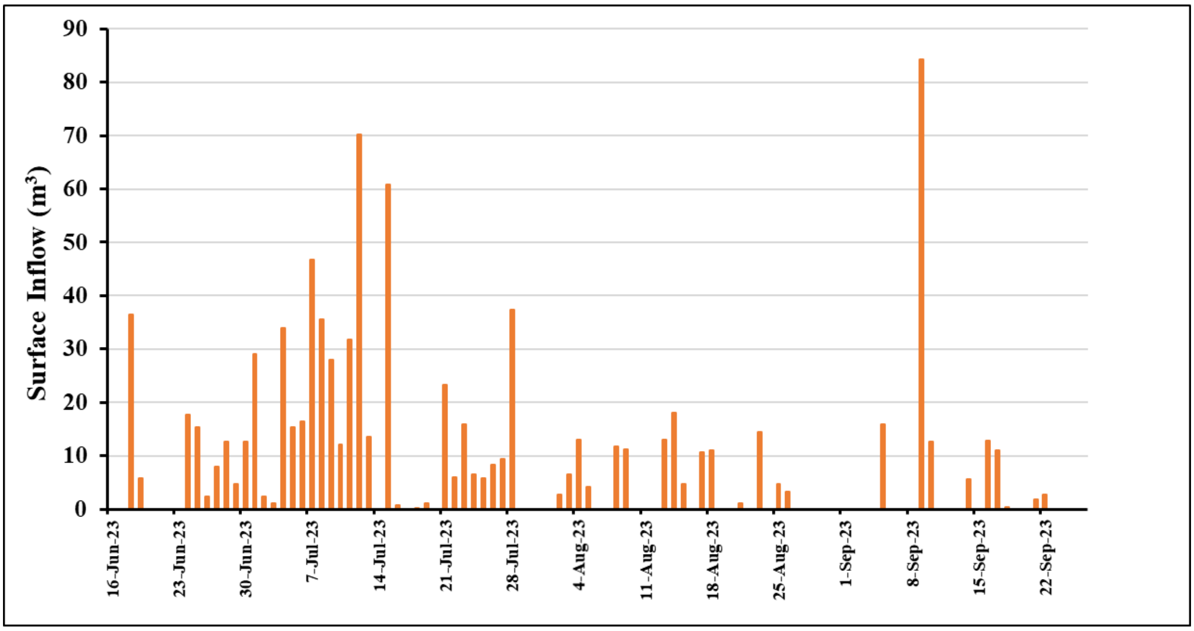

Figure 22: Estimated surface runoff for Badrish Lake

6.3.3 Out-flow due to evaporation losses

Volume of water lost due to evaporation from the lake in different months has been estimated by applying the average evaporation rates for a month to the average surface area of the lake during that month. The evaporation losses from the lake Shesh Netra varies from 101.1 m^3

in June month to 359.6 m^3 during August month. Similarly, for the Badrish lake, evaporation losses vary from 38.7 m^3 in June 2023 to 135.4 m^3 during August, 2023.

6.3.4 Net groundwater flow

In the water balance equation discussed earlier, the terms change in storage; ΔS, Evaporation losses; O_E, Surface runoff; I_s and direct rainfall over the lake; I_P are known. Ground water inflow; I_G and ground water outflow; O_G are not known. So, net ground water flow to the lakes have been estimated as the as the residual term of the water balance equation as:

$$I_G - O_G = \Delta S + O_E - (I_s + I_P)$$

The net ground water flow for the lake Shesh Netra varies from -5056.5 m^3 in July, 2023 to -757.2 m^3 during June, 2023. The negative sign indicates that GW outflow is more that GW inflow. Similarly, for the Badrish lake, the net ground water flow vary from -2712.7 m^3 in July 2023 to -574.2 m^3 during August, 2023.

6.3.5 Change in lake storage

The net change in lake storage can be easily calculated from water levels of the lake if the depth-area-capacity curve called hypsographic curve, is available for the lake. Such a curve has been prepared for the lake using the data of the bathymetric survey carried out during the present study. These have been presented in the chapter on Lake Bathymetry. A contour map was first prepared from the survey and the hypsographic curve was then developed from the contour map. The hypsographic curve directly gives the storage capacity (volume) of water in the lake corresponding to a water level. The change in storage capacity (volume) of the lake during a specific period can be calculated by finding out the difference in volumes of water at two different water levels in the lake at the beginning and end of the period, to get the change in lake storage during that period.

Figure 23 presents the change in storage of the lake estimated for different months for the Shesh Netra lake while ***Figure 24*** presents the data for the Badrish lake. It can be easily seen that the change in lake storage varies from month to month, owing to variations in the inflow and outflow components. During the period of observation (June to September, 2023), maximum increase in lake storage of 1770.4 for Shesh Netra lake was observed during the month of July, 2023. As far as Badrish lake is concerned, the maximum increase in lake storage of 469.1 was observed during the month of July 2023. Decline in lake storage was observed during August and September, 2023 for Sheh Netra lake while decline in lake storage was observed for Badrish lake during June and September 2023.

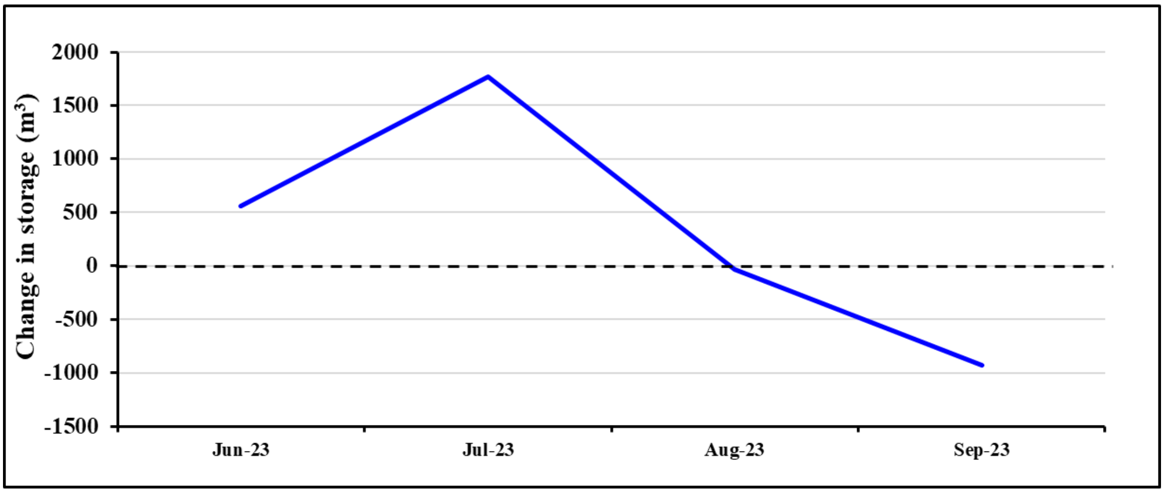

Figure 23: Change in lake storage during different months for Shesh Netra lake

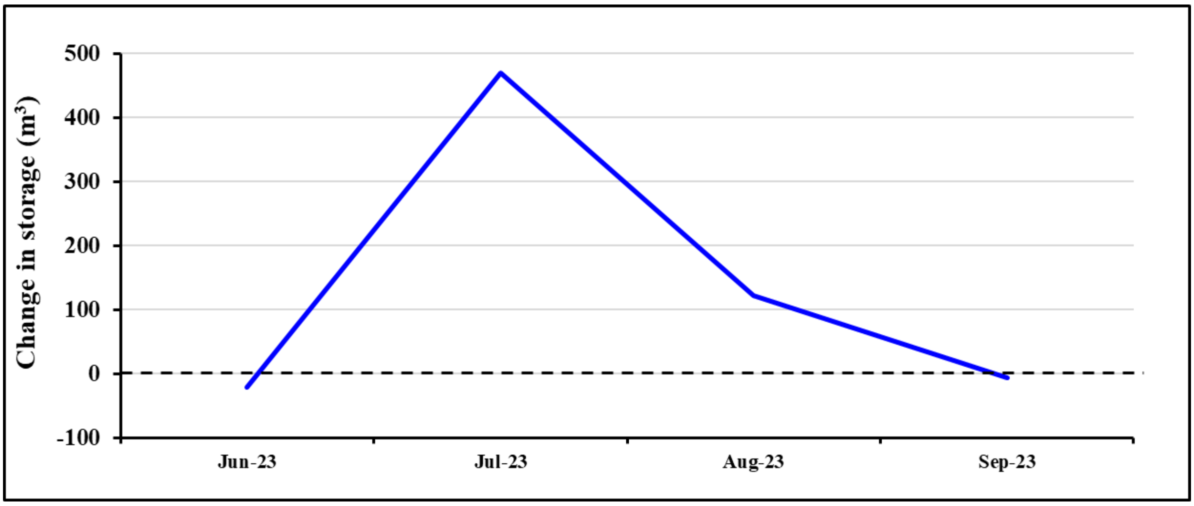

Figure 24: Change in lake storage during different months for Badrish lake

The estimated water balance for Shesh Netra Lake is given in ***Table 3*** and the estimated water balance for Badrish Lake is given in ***Table 4***.

Table 3: Water balance of the Shesh Netra

Month	Avg. Water Level (m)	Rainfall (mm)	Change in Storage (m^3)	Direct Rain Over Lake (m^3)	Runoff (m3)	Lake Evaporation (m^3/month)	Net Groundwater Flow (m^3)
Jun-2023	1.61	44.1	561.66	206.2	1213.8	101.1	-757.2
Jul-2023	1.91	222	1770.37	1038.0	6110.2	321.4	-5056.5
Aug-2023	2.07	55.9	-33.44	261.4	1538.7	359.6	-1473.7
Sep-2023	1.98	63	-931.06	294.6	1734.0	269.5	-2690.1

Table 4: Water balance of the Badrish lake

Month	Avg. Water Level (m)	Rainfall (mm)	Change in Storage (m^3)	Direct Rain Over Lake (m^3)	Runoff (m3)	Lake Evaporation (m^3/month)	Net Groundwater Flow (m^3)
Jun-2023	1.30	44.1	-20.93	140.1	515.78	38.74	-638.06
Jul-2023	1.12	222	469.11	705.2	2596.47	119.85	-2712.68
Aug-2023	1.00	55.9	121.77	177.6	653.80	135.42	-574.17
Sep-2023	0.95	63	-6.58	200.1	736.84	112.43	-831.10

6.2 Factors determining the hydrological behaviour of the lakes

As has been mentioned earlier, lake water level variation is an indicator of the hydrological behaviour of the lake. Water levels reached by a lake affects the total water storage in the lake. The lake water level and consequently, the lake storage is affected by factors such as inflows to the lake and outflows from the lake. As such, detailed analysis of the lake water level variation or variation in lake storage is important for any lake to understand its hydrological behaviour. In general, the change in lake storage is generally positive during the rainy months indicating that the total inflow is generally higher in these months than the total losses. During the non-rainy months when there is no rainfall, the inflow from catchment as surface runoff is either negligible or almost zero. The net change in lake storage is, therefore, generally negative indicating that total losses from the lake are higher than the total inflow to the lake. However, this is a general behaviour but may not be true for all the lakes, as each lake is a different entity regarding its hydrology. Particularly, lakes with significant ground water inflows or outflows or both, may have a totally different hydrological behaviours.

Variation in lake water levels have been discussed in previous section. Efforts have been made to analyze the factors responsible for change in lake storage during different months., for both the lakes. These are discussed below.

Figure 25 presents the relationship between variation in lake storage and rainfall during different months for the Shesh Netra lake while ***Figure 26*** presents the relationship between variation in lake storage and volume of water added to the lake by rainfall falling directly over the lake. Similarly, ***Figure 27*** presents the relationship between variation in lake storage and surface runoff to the Shesh Netra lake. From the ***Figure 25*** it is clear that during the rainy months of June to September, 2023 change in lake storage in a month is influenced by rainfall. For example, the month of July which shows highest rainfall of the four months, also shows maximum rise in lake storage. However, on the other hand it is also observed that change in lake storage in a month is not completely influenced by the rainfall falling in that month. For example, while rainfall in the months of June and July increases the lake storage for Sheh Netra lake, further rainfall during the month of August and September, do not increase the lake storage and there is a decline in lake storage after August. Also, despite higher rain during the month of September compared to August, a decline in lake storage was observed. This indicates that the ground water outflow from the lake is higher than the combined magnitude of ground water inflow, direct rainfall and runoff. Thus, it can be inferred that the change in lake storage is not determined by rainfall alone and groundwater component also plays an important role. Since runoff to the lake as well as direct rainfall over the lake is also determined by the rainfall, ***Figures 26 and 27*** also exhibit similar results.

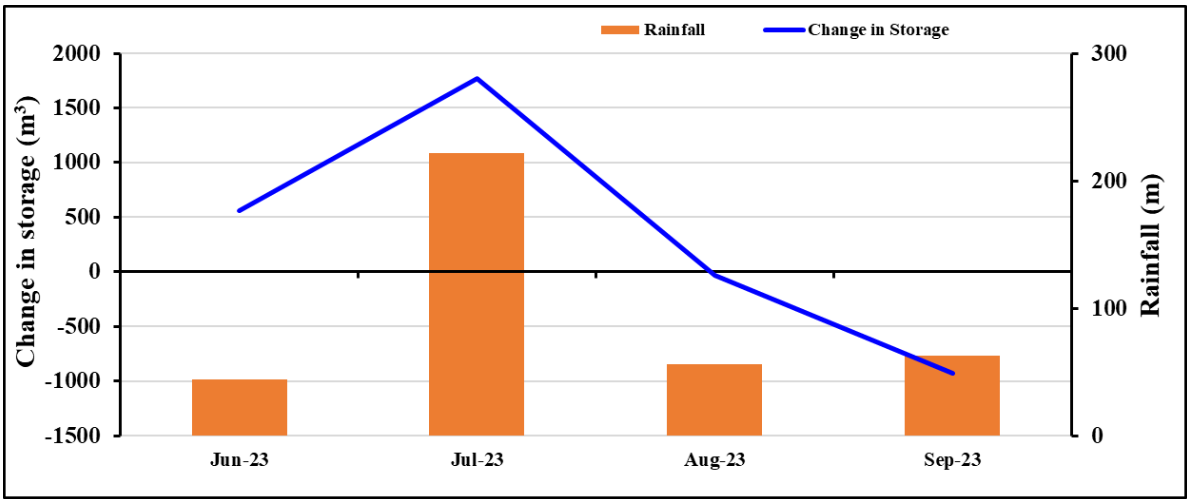

Figure 25: Change in lake storage with respect to rainfall in the lake catchment for Shesh Netra lake

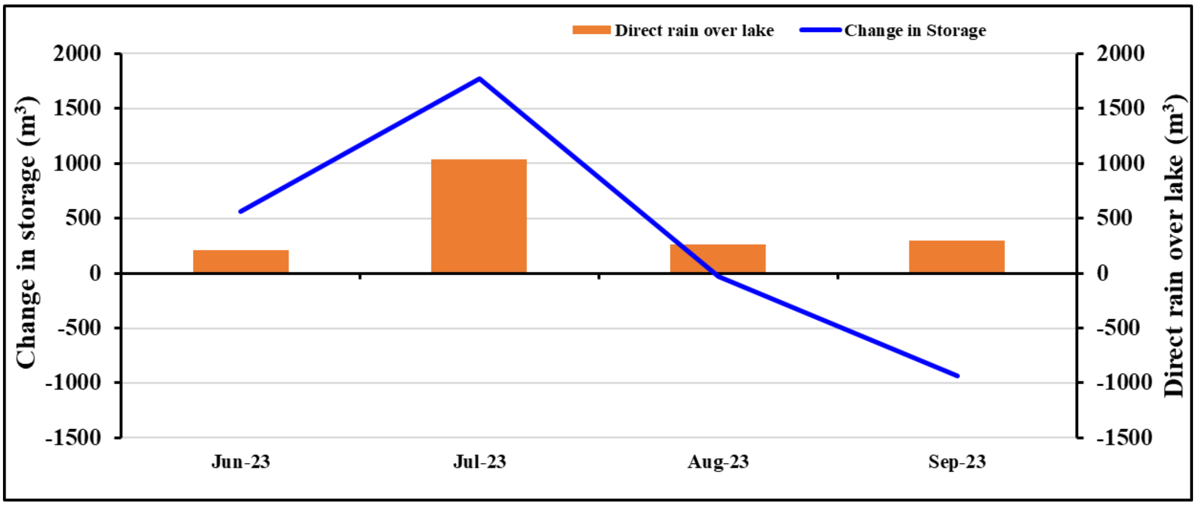

Figure 26: Change in lake storage with respect to volume of water added due to rain falling directly over the Shesh Netra lake

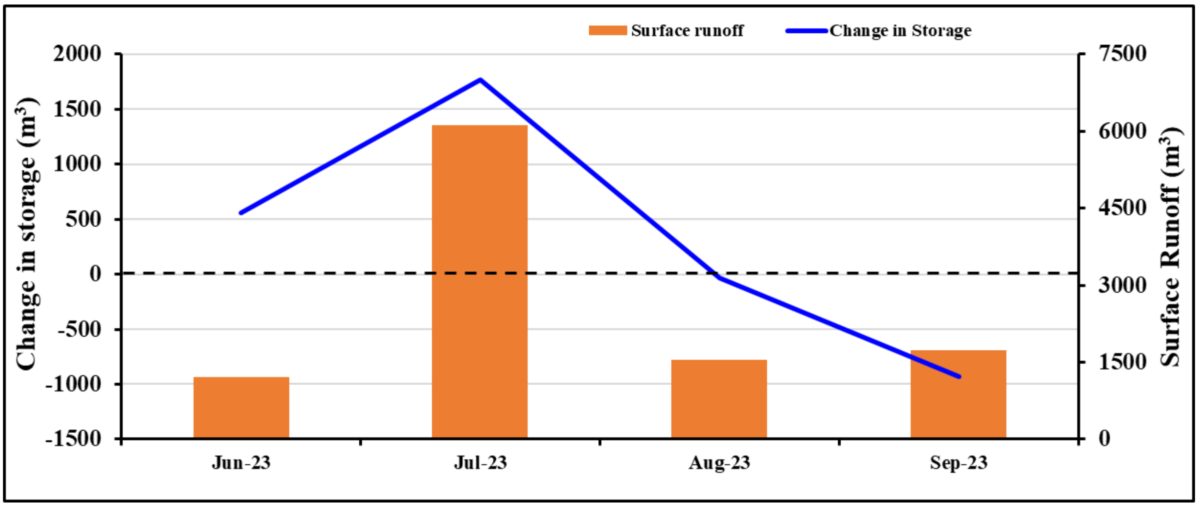

Figure 27: Change in lake storage with respect to surface runoff for Shesh Netra lake

Similar results are also exhibited by Badrish lake as can be seen in ***Figure 28***, ***Figure 29*** and ***Figure 30***.

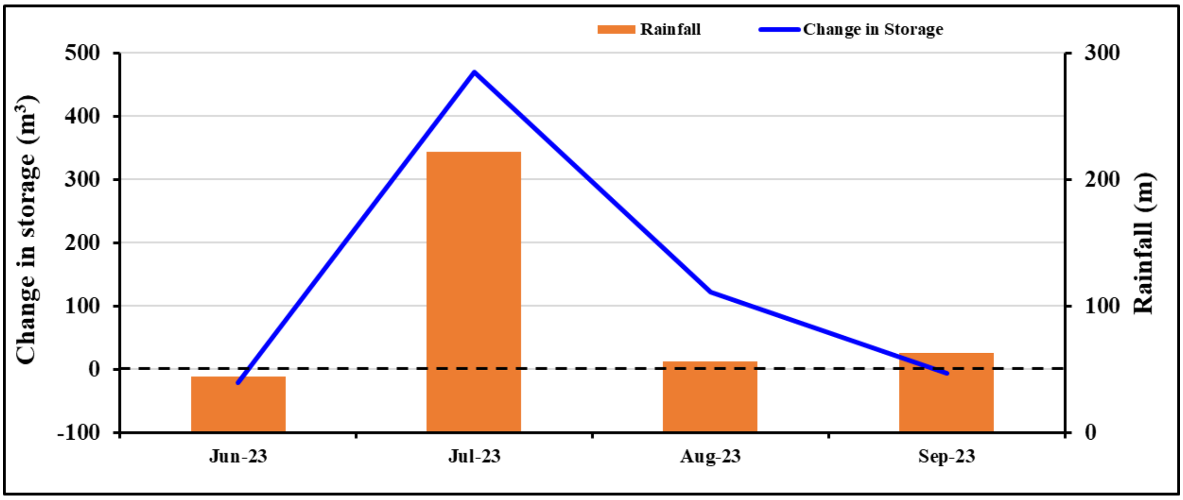

Figure 28: Change in lake storage with respect to rainfall in the lake catchment for Badrish lake

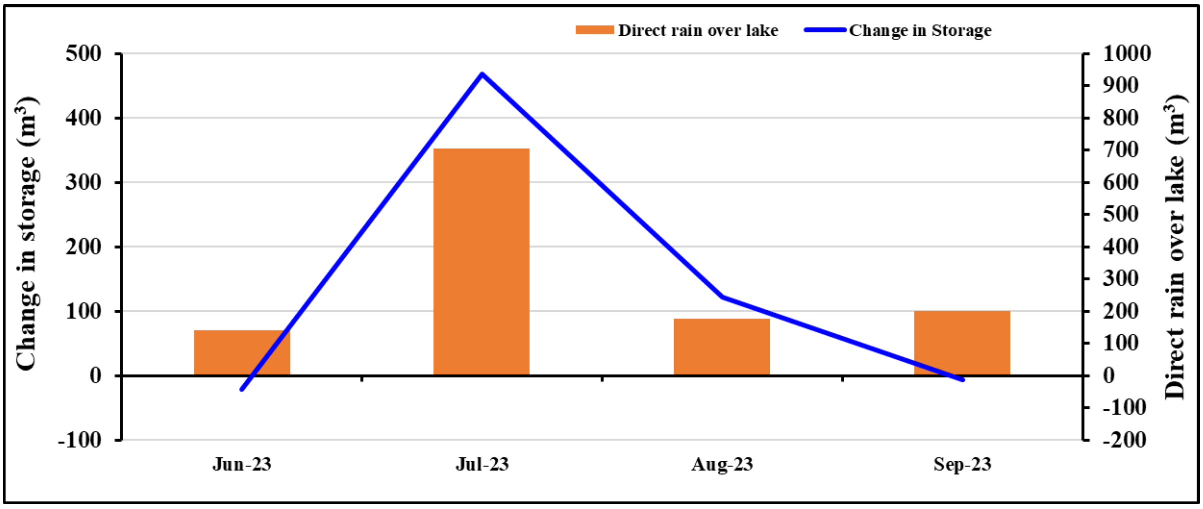

Figure 29: Change in lake storage with respect to volume of water added due to rain falling directly over Badrish lake

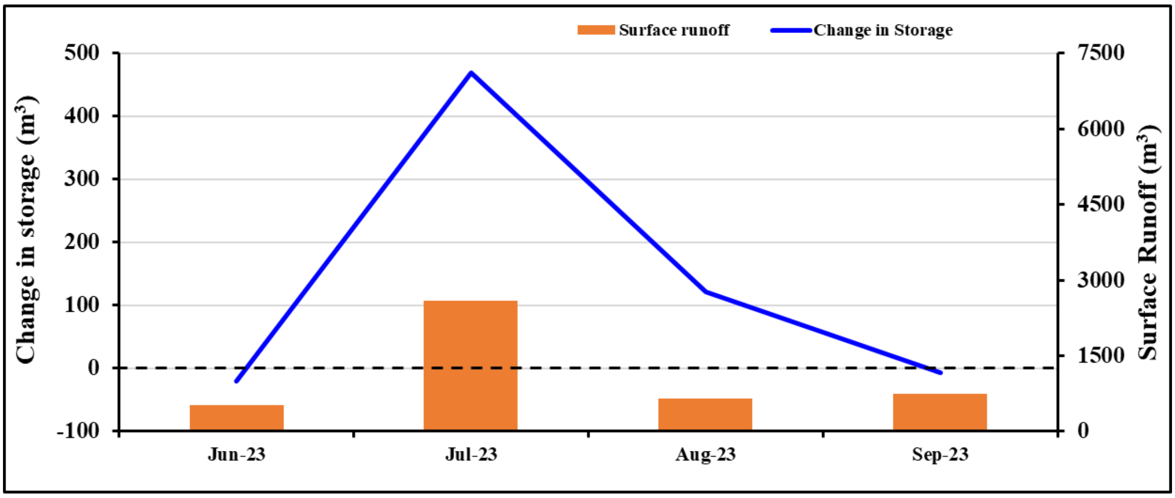

Figure 30: Change in lake storage with respect to surface runoff for Badrish lake

Although, being a high altitude lake, evaporation is not expected to be significant enough to determine the lake storage, though it may have a positive correlation with the lake storage, as can be generally seen from ***Figure 31*** for Shesh Netra lake and ***Figure 32*** for Badrish lake, which show that there is decline in lake storage when the evaporation losses are higher. However, it must be noted that it is just a positive correlation and in reality since the evaporation losses are significantly less compared to the other inflow and outflow parameters, they are not likely to be the major cause determining the lake storage.

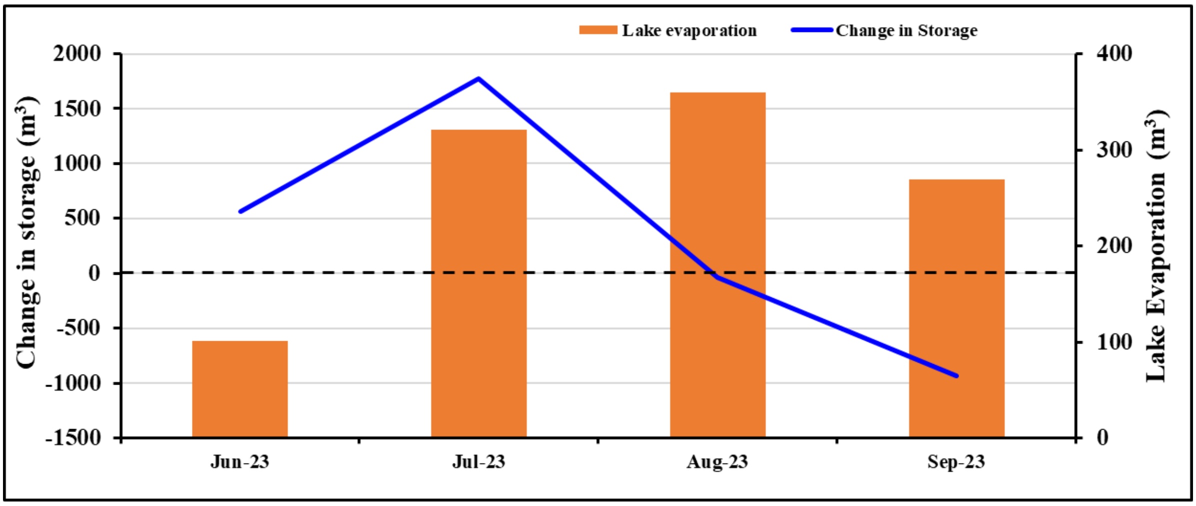

Figure 31: Change in lake storage with respect to lake evaporation for Shesh Netra lake

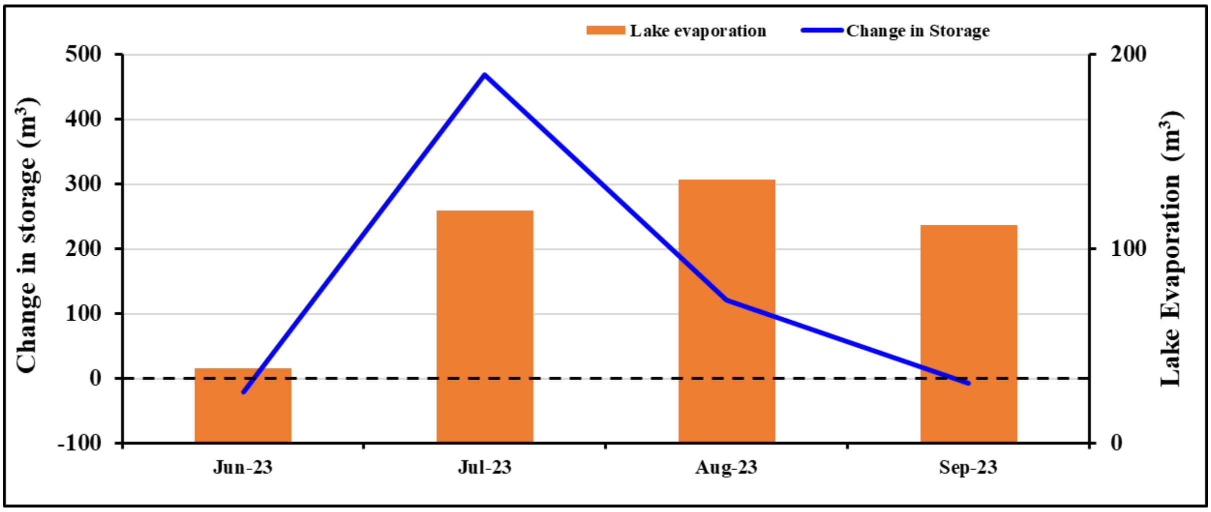

Figure 32: Change in lake storage with respect to lake evaporation for Badrish lake

Figure 33 provides the graph of change in lake storage versus net ground water flow for the Shesh Netra lake. As a reminder, net ground water balance has been estimated as a residual component of the lake water balance (as all other terms are known). It can be seen from the ***Figure 33*** that there does not exist a positive correlation between the two, during the rainy months of June to September, as lake storage in these months are significantly influenced by rainfall also. Improvement in net GW flow (with more GW inflow and less GW outflow) is observed to maintain the lake water level in both the lakes. Further, it also implies that during the non-rainy months (for which no rainfall data are available and hence no wate balance could be carried out) the lake storage is more or less determined by the net GW flow, thereby maintaining the lake water levels.

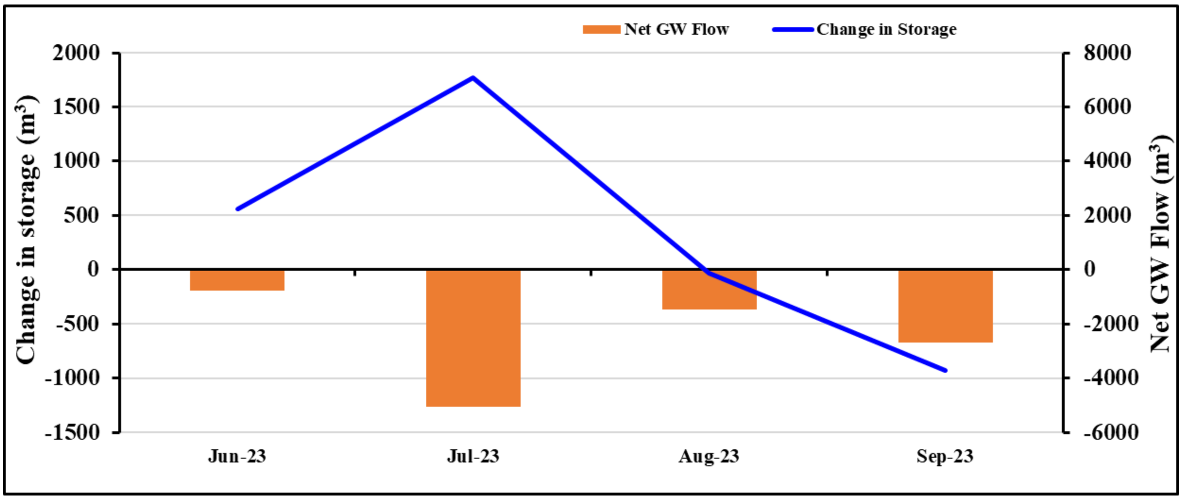

Figure 33: Change in lake storage with respect to net groundwater flow for Shesh Netra lake

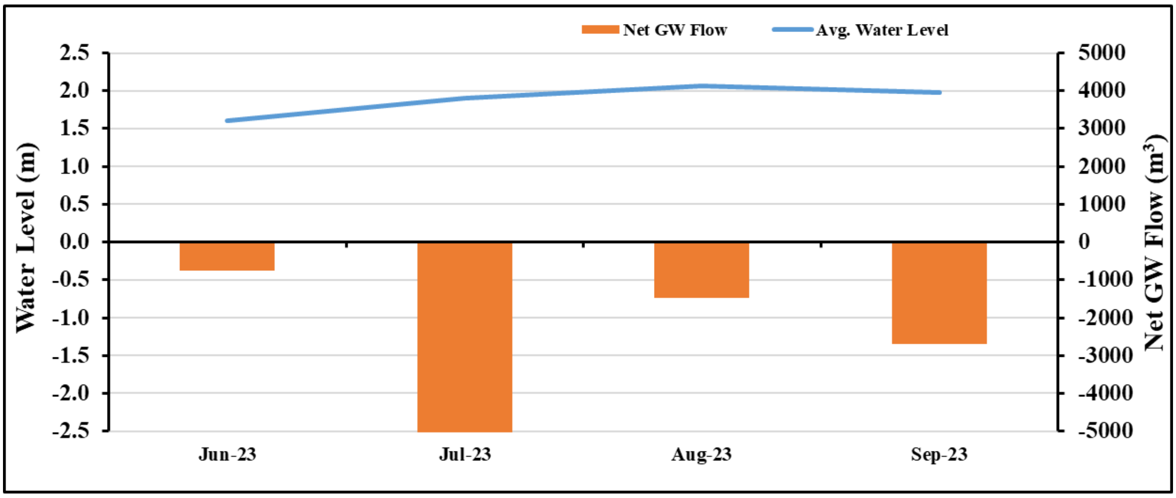

Figure 34: Variation of average water level with respect of net groundwater flow in Shesh Netra lake

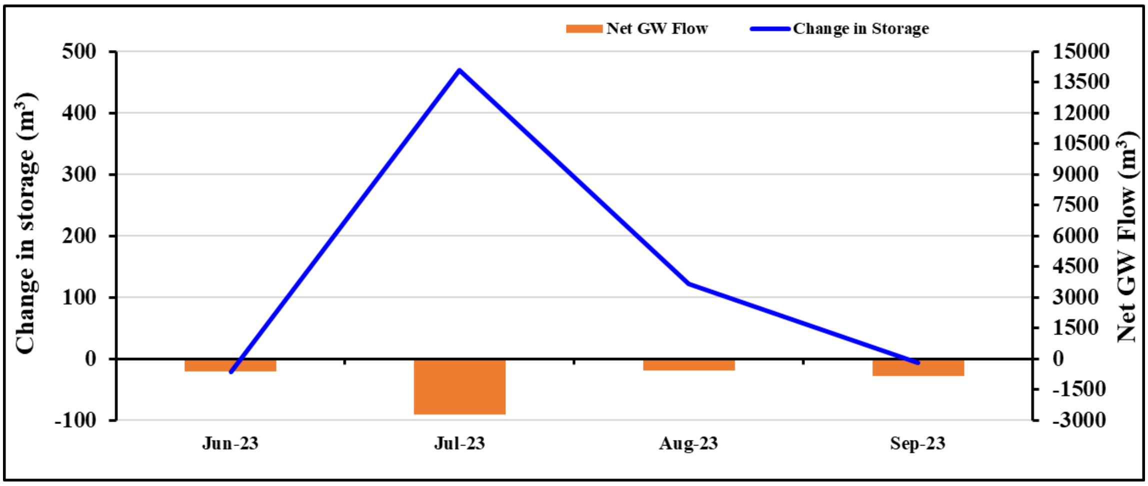

Figure 35: Change in lake storage with respect to net groundwater flow in Badrish lake

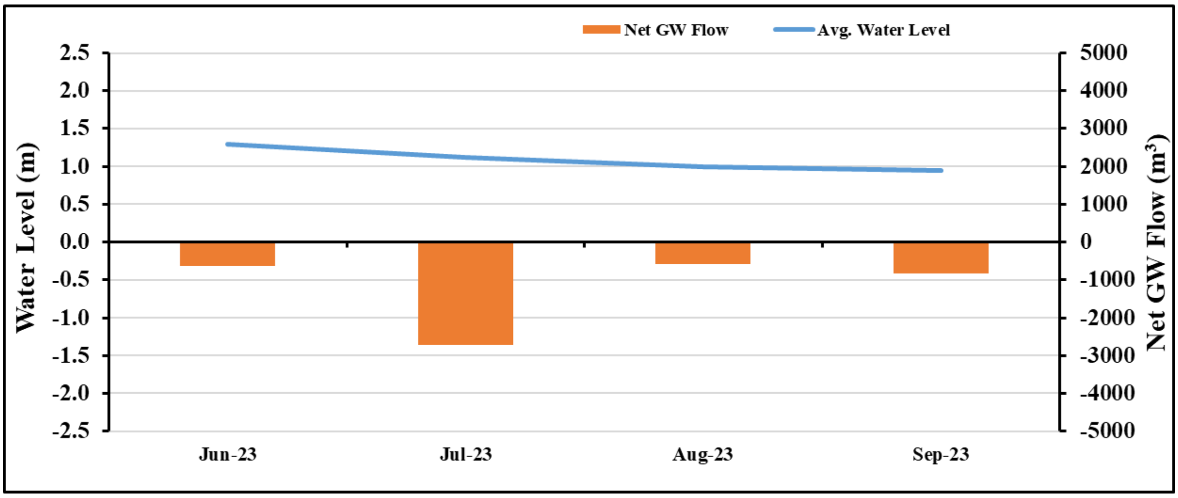

Figure 36: Variation of average water level with respect to net groundwater flow in Badrish lake

7.0 IDENTIFICATION OF SOURCE OF WATER

Under the study, isotopic investigations have been carried out for identification of source of water and estimation of relative contribution of different sources to the lake water, for both the lakes. Environmental isotopes such as ^{18}O and ^{2}H have been used for the purpose. They are considered as ideal tracers. Environmental isotopes are the stable isotopes that are available in the environment and introduced in the hydrological cycle naturally. Thus, it is not required to inject them into the system for carrying out hydrological studies. Variations in isotopic signatures of different sources of water are analysed to interpret the hydrological processes. The isotope variations result from isotope fractionation which occurs during various physical and chemical processes. Measurements of stable isotopes are done in terms of abundance ratios i.e. atomic mass of heavy atom to the atomic mass of light atom. The relative difference in the ratio of the heavy isotopes to the more abundant light isotope of the sample with respect to a reference is determined. The difference is designated as δ. The difference between the sample and the reference is usually quite small, δ values are therefore, expressed in per mille differences (‰) i.e. per thousand, δ (‰) = $\delta \times 1000$. If the δ value is positive, it refers to the enrichment of the sample in the heavy-isotope species with respect to the reference and negative value corresponds to the depletion in the heavy-isotope species. The reference standard normally considered is VSMOW (Vienna Standard Mean Ocean Water).

Under the present study, water sampling for isotopic analysis of lakes and other water sources in Badrinath had been carried out considering the topography, morphometry and availability of sources of water. Accordingly, water samples have been collected from rain, snow, surface water (river, lakes and dhara) and springs for stable isotopic analysis.

As far as rainfall samples are concerned, no samples could be collected during the monsoon season of 2022. So, for the purpose of investigations, the isotopic data of rain samples collected for Badrinath by NIH during 2023 (June-September) only have been used to understand the variation in the isotopic signatures of rainfall. Event-based rain samples have been collected in the study from the ordinary rain gauge station installed in the study area under the study. Samples of surface waters and ground waters have been collected on weakly basis. The samples have been collected from 7 locations. Out of these 7 samples locations, 2 are from the two lakes, 1 sample each from Alaknanda river, Tapt Kund and Rishi dhara and 2 from springs namely Prahlad Dhara and Kurmi Dhara. The details of sampling locations are shown in ***Table 5***.

Table 5: Sampling sites for isotopic analysis of Badrinath lakes and surrounding waters sources

S.N.	Source	Location	Latitude	Longitude
1	Rishi Dhara	Badrinath	30.741248	79.491077
2	Kurm Dhara	Badrinath	30.744270	79.490942
3	Pralhad Dhara	Badrinath	30.744675	79.491037
4	Tapt Kund	Badrinath	30.744798	79.491610
5	River	Alaknanda River	30.745495	79.491675
6	Lake	Shesh Netra Lake	30.743238	79.493862
7	Lake	Badrish Lake	30.745272	79.496182

The water samples were collected in pre-cleaned high density polythene bottle (HTPE) (20 ml) for stable isotopic measurements. The bottles were rinsed twice at the sampling site with the sample water to avoid mixing and evaporative enrichment during the sampling. Further, to prevent any evaporative losses from the sample bottles, bottles were tightly sealed and brought to the laboratory for stable isotopic analysis. The isotopic analysis was carried at the Nuclear Hydrology Laboratory of NIH, Roorkee.

7.1 Results of Isotopic Analysis

7.1.1 Precipitation

Figure 37 presents the isotopic characteristics of precipitation at Badrinath. The isotopic signatures vary from -23.1‰ to 0.4‰ for $\delta^{18}O$ and -181.9‰ to 15.8‰ for δ^2H. The regression analysis between $\delta^{18}O$ and δ^2H of the data gives the best fit line (LMWL) for different sources as follows:

$$\delta^2H= (8.28 \times \delta^{18}O + 15.31, (n = 58, R^2 = 0.99)$$

Where, n is the number of samples and r is the correlation coefficient. The best-fit lines of LMWL is showing high slope and intercept with respect to GMWL. The high slope of LMWL appears to be due to the low air temperature and snow precipitation, while the evaporative enrichment of δ^2H at low temperature may be a reason for the higher intercept (Kumar et al., 2010). Higher intercept suggests the change in moisture source due to western disturbances which is indicated by higher d-excess (Yurtsever and Gat, 1981).

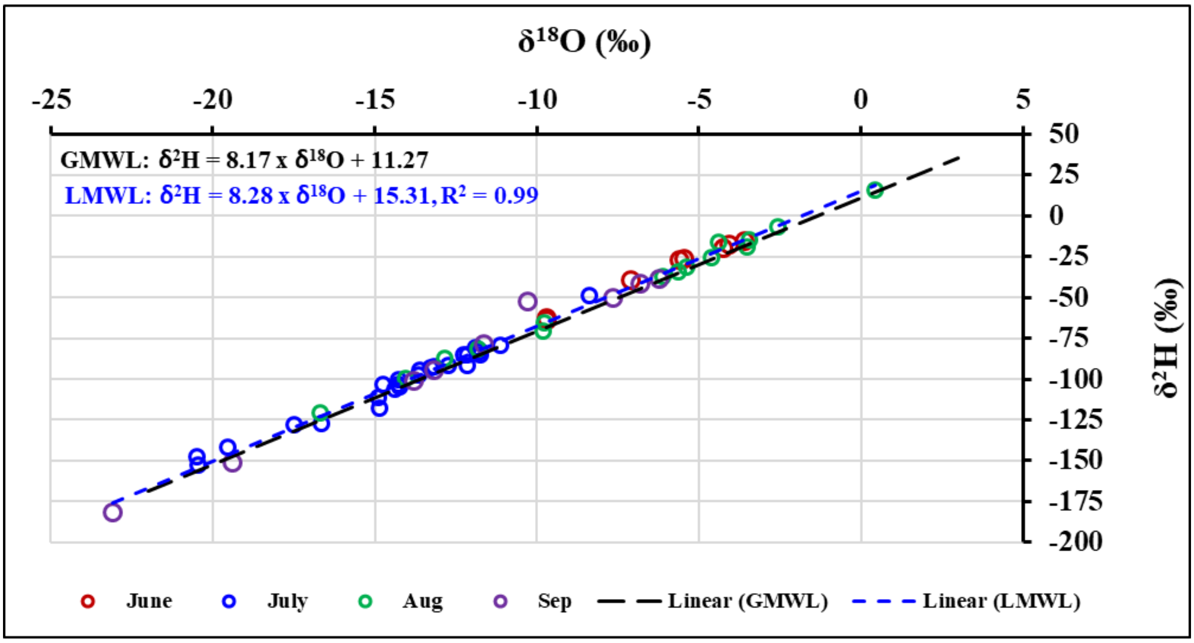

Figure 37: Isotopic characteristics of rainfall at Badrinath

The d-excess of precipitation has been determined (***Figure 38***). It is observed to vary from 1.3‰ to 29.5‰ with an average of 12.3‰. As far as monthly variation in d-excess is concerned, in June month it varies from 13.1‰ to 17.8‰ with an average of 15.4‰, in July month it varied from 1.3‰ to 18.2‰ with an average of 11.3‰, in August month it varied from 8.0‰ to 18.7‰ with an average of 12.6‰ and in September month it varied from 2.8‰ to 29.5‰ with an average of 11.8‰ The d-excess value of the study region reflects the trend of Northern hemisphere (Froehlich et al. 2002) with 5‰ to 12‰ values during the summer monsoon periods. The higher amount of d-excess is similar to that of the isotopic composition at the western side of Himalayas, i.e. at Indus River Basin (Pande et al. 2000) and might be due to moisture source from Mediterranean region (***Figure 38***).

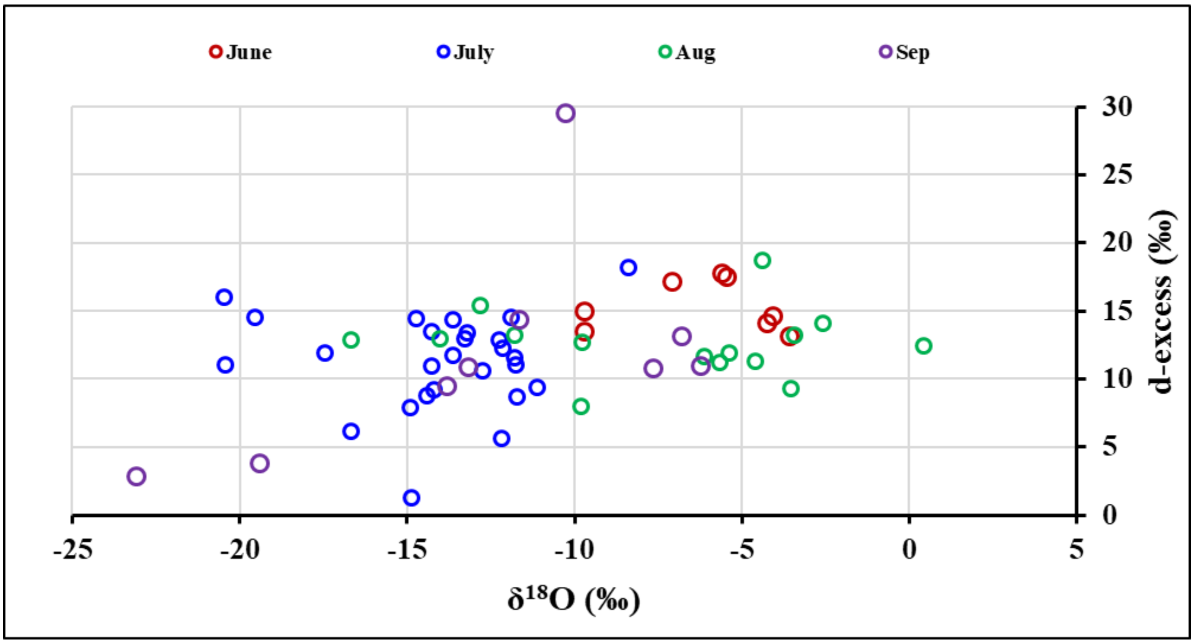

Figure 38: $\delta^{18}O$ vs d-excess plot of rainfall at Badrinath

7.1.2 Lakes and surrounding waters

The isotope composition of the lakes and various sources of water around the lakes have been determined. The isotopic composition of Anaknanda river at Badrinath varies from -17.0‰ to -12.6‰ for $\delta^{18}O$ and from -118.8‰ to -82.5‰ for $\delta^{2}H$, in Rishi dhara the isotopic composition varies from -14.7‰ to -9.8‰ for $\delta^{18}O$ and -96.9‰ to -59.0‰ for $\delta^{2}H$. The isotopic composition of Pralhad dhara varies from -12.4‰ to -10.9‰ for $\delta^{18}O$ and -82.2‰ to -68.9‰ for $\delta^{2}H$. The isotopic composition of Kurm dhara varies from -11.3‰ to -11.1‰ for $\delta^{18}O$ and -71.9‰ to -69.6‰ for $\delta^{2}H$. The the isotopic composition of Tapt Kund varies from -13.8‰ to -13.1‰ for $\delta^{18}O$ and -97.0‰ to -93.3‰ for $\delta^{2}H$. As far as the lakes are concerned, the isotopic composition varies from -12.6‰ to -4.7‰ for $\delta^{18}O$ and -94.8‰ to -36.7‰ for $\delta^{2}H$ for the Shesh Netra lake and from -13.6‰ to -5.4‰ for $\delta^{18}O$ and -99.8‰ to -37.8‰ for $\delta^{2}H$ for Badrish lake. The isotopic composition of the two lakes are shown in ***Figure 39*** and ***Figure 40*** respectively. From the ***Figures 39*** and ***40*** it is evident that the isotopic signatures of lakes are showing lower slope and intercept with respect to LMWL due to evaporative enrichment of the lake water.

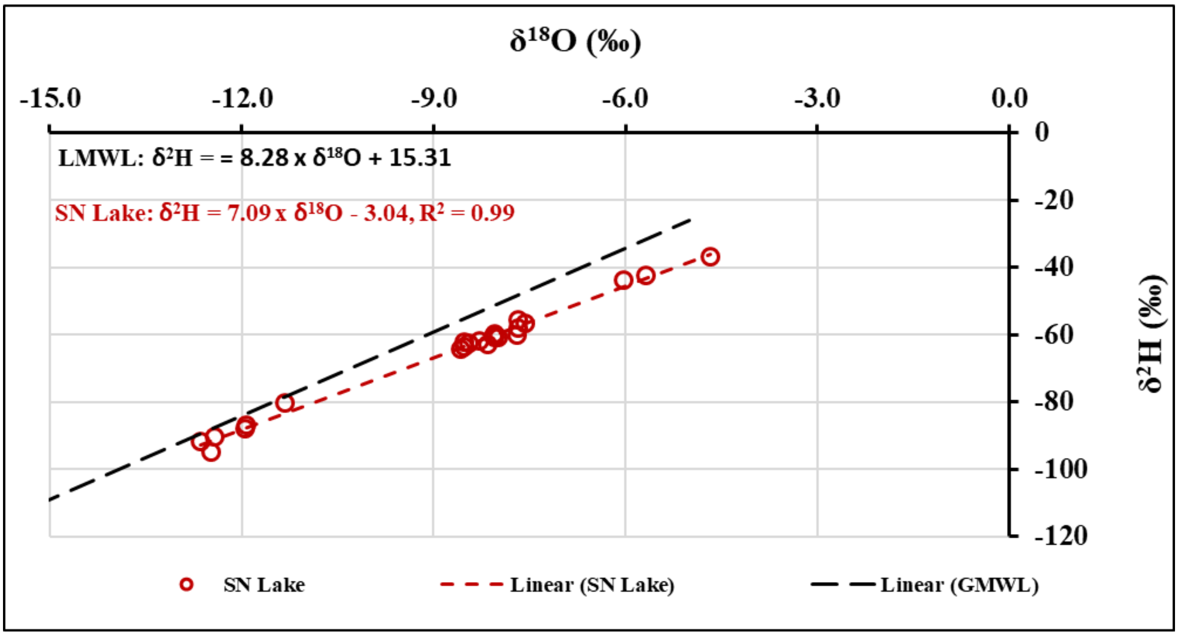

Figure 39: Isotopic characteristics of Shesh Netra lake

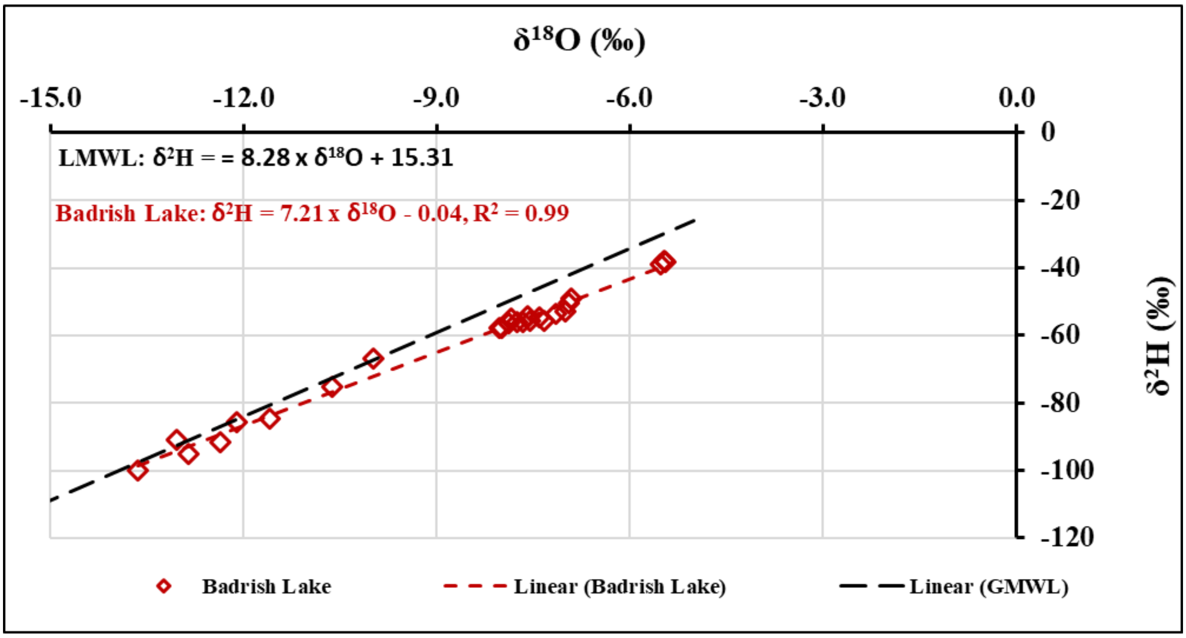

Figure 40: Isotopic characteristics of Badrish lake

For the estimation of the relative contribution of various sources such as runoff, ground water and snow isotopic signatures of all the sources pertaining to the same season are required. For the estimation of contribution of different component in Shesh Netra lake, the monthly average groundwater value of $\delta^{18}O$ are -10.89‰, -11.13‰, -11.13‰ and -11.17‰ in June, July, August and September respectively, for the lake the monthly average value of $\delta^{18}O$ are -5.58‰, -8.08‰, -8.25‰ and -8.05‰ in June, July, August and September respectively and for rain, the monthly average value of $\delta^{18}O$ are -5.58‰, -15.29‰, -13.58‰ and -16.58‰ in June, July, August and September respectively. Its corresponding values of EC are 172 µS/cm, 103 µS/cm, 83 µS/cm and 94 µS/cm respectively in groundwater. The values of EC are 40 µS/cm, 126 µS/cm, 137 µS/cm and 111 µS/cm respectively for lake water and for rain water, the corresponding EC values are 53 µS/cm, 22 µS/cm, 31 µS/cm and 31 µS/cm respectively. The $\delta^{18}O$ and EC value of snow is -6.7‰ and 20 µS/cm respectively. The contribution of groundwater, snow and rain to the lake have been estimated based on the average monthly data using the three box model. As per the analysis carried out under the study using the monthly average data, the contribution of groundwater, snow and rain is estimated to be 22%, 22% and 55% in June month, 62%, 22% and 16% in July month, 70%, 5% and 25% in August month and 70%, 15% and 15% in September month (***Figure 41***).

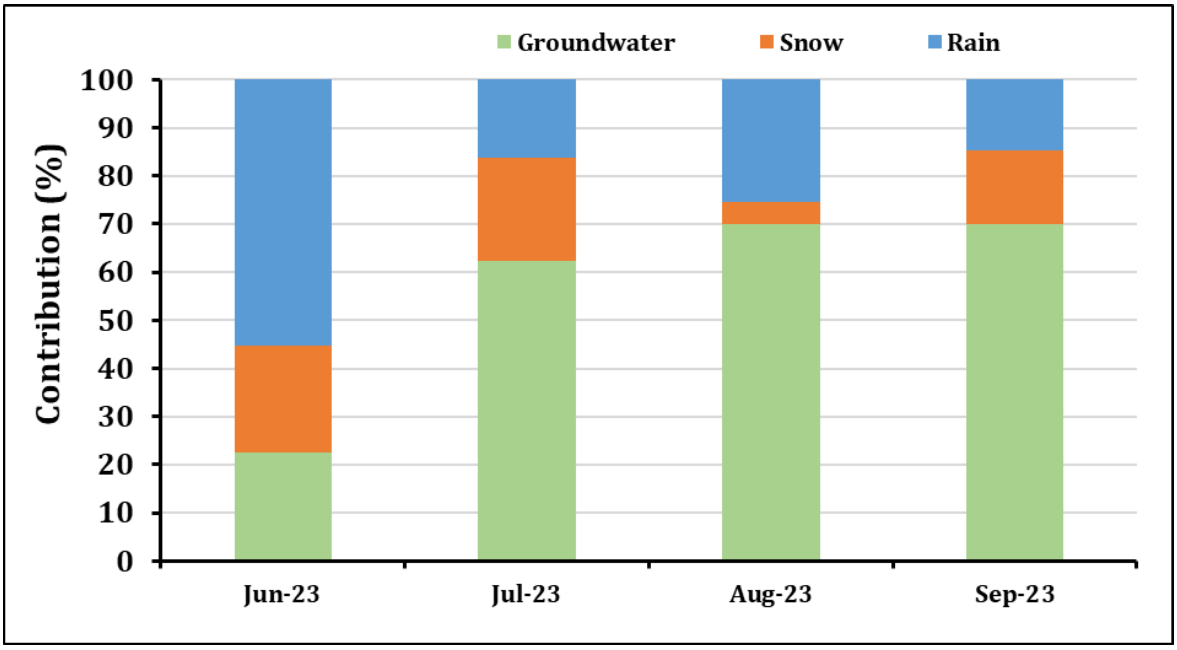

Figure 41: The estimated contribution of groundwater, snow and rain to Shesh Netra lake

For Badrish lake, for the estimation of contribution of different sources, the monthly average lake water values of $\delta^{18}O$ for June, July, August and September are -5.27‰, -7.50‰, -7.64‰ and -7.39‰ respectively and its corresponding values of EC are 40 µS/cm, 131 µS/cm, 139 µS/cm and 135 µS/cm respectively. The $\delta^{18}O$ and EC value of groundwater, snow and rain water are same as Shesh Netra lake. As per the analysis analysis carried out under the study using the monthly average data, the contribution of groundwater, snow and rain is estimated to be 21%, 18% and 61% for June month, 74%, 15% and 11% for July month, 73%, 12% and 15% for August month and 80%, 13% and 7% for September month (***Figure 42***).

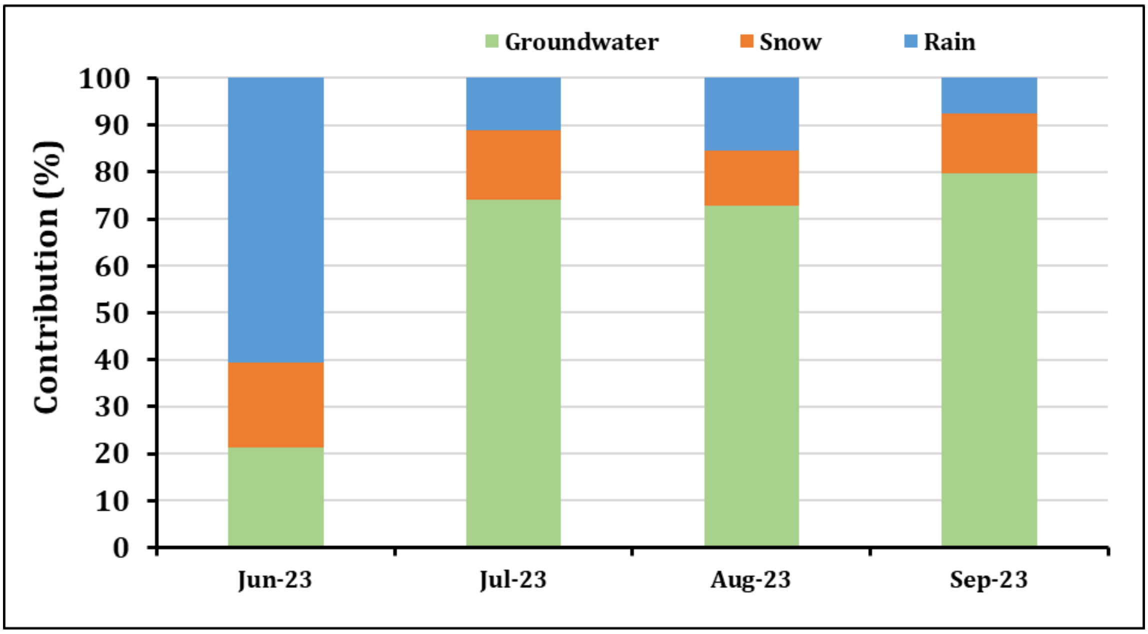

Figure 42: The estimated contribution of groundwater, snow and rain to Badrish lake

8.0 WATER QUALITY ASPECTS

During the present study, water quality of the lakes was also monitored for the pre-monsoon period of June 2022. Water samples were analyzed for physical paramters such as pH, EC, TDS, major cations (Ca, Mg, Na, K, and NH_4), major anions (F, Cl, HCO_3, SO_4, and NO_3). Temperature was measured in-situ while all the other parameters were analysed following Standard Methods for the Examination of Water and Wastewater (APHA, 1995). All anions and cations were analyzed on Metrohm Make Ion Chromatograph (IC) Model 930 (for anions and cations) and Potentiometric Auto Titrator Model 888 system (for bicarbonate). All the laboratory analysis was carried out at the National Institute of Hydrology, Roorkee. ***Table 6, 8*** and ***10*** presents the physical parameters of the lakes while ***Table 7, 9*** and ***11*** presents the major ions.

Table 6: Physical parameters of Badrinath lakes during June 2022

S. N.	Location	Temp ^0C	pH	EC µS/cm	TDS mg/l	Alk mg/l	Hard mg/l
1.	Shesh Netra Lake	17.5	8.0	165	111	53.8	57.1
2.	Badrish Lake	14.9	7.8	145	82	51.4	57.8

Table 7: Major ions in Badrinath lakes during June 2022

S. N.	Location	F^- mg/l	Cl^- mg/l	HCO_3^- mg/l	SO_4^{2-} mg/l	NO_3^- mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^+ mg/l	K^+ mg/l	NH_4^+ mg/l
1	Shesh Netra Lake	0.05	10.63	65.64	18.41	0.37	19.46	2.05	6.80	4.92	1.59
2	Badrish Lake	0.06	2.71	62.712	18.47	0.47	20.16	1.82	4.25	2.81	1.10

Table 8: Physical parameters of Badrinath lakes during June-2023

S. N.	Location	Temp ^0C	pH	EC µS/cm	TDS mg/l	Alk mg/l	Hard mg/l
1.	Shesh Netra Lake	20.1	9.8	206	124	66.1	67.1
2.	Badrish Lake	18.2	7.8	311	187	76.0	75.6

Table 9: Major ions in Badrinath lakes during June-2023

S. N.	Location	F^- mg/l	Cl^- mg/l	HCO_3^- mg/l	SO_4^{2-} mg/l	NO_3^- mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^+ mg/l	K^+ mg/l	NH_4^+ mg/l
1	Shesh Netra Lake	0.29	4.60	80.64	24.36	0.79	24.87	1.19	10.19	17.52	
2	Badrish Lake	0.21	6.94	92.712	18.59	1.28	26.32	2.40	10.60	16.83	0.67

Table 10: Physical parameters of Badrinath lakes during September-2023

S. N.	Location	Temp ^0C	pH	EC µS/cm	TDS mg/l	Alk mg/l	Hard mg/l
1.	Shesh Netra Lake		7.8	172	92.9	63.6	68.3
2.	Badrish Lake		7.7	104	56.2	74.4	87.2

Table 11: Major ions in Badrinath lakes during September-2023

S. N.	Location	F^- mg/l	Cl^- mg/l	HCO_3^- mg/l	SO_4^{2-} mg/l	NO_3^- mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	Na^+ mg/l	K^+ mg/l	NH_4^+ mg/l
1	Shesh Netra Lake	0.18	9.96	77.64	25.16	0.63	24.82	1.53	13.43	15.44	0.23
2	Badrish Lake	0.17	6.81	90.71	14.67	0.88	30.83	2.46	9.07	10.71	0.13

It is observed that all the water quality parameters for both the lakes are well within the acceptable limits prescribed by BIS.

9.0 CONCLUDING OBSERVATIONS

Based on the preliminary investigations carried out so far with the limited available data following observations are made:

i) Bathymetric survey of the lakes has been carried out and morphometric characterization of the lakes have been done. Also, development of depth area capacity curves for the lakes is under is under progress. Automatic water level recorder has been installed in the lake for generation of lake water level data. Similarly, ordinary rain gauge has been installed in the study area to monitor rainfall as well as for collection of rainfall samples. Data observer has been appointed for collection of regular samples from the various sources in the study area.

ii) Morphometric analysis of the lakes based on the bathymetry data indicates that the maximum depth of the Shesh Netra lake is 2.42 m while its mean depth is observed to be 1.81 m. The maximum depth of the Badrish lake is 2.57 m while its mean depth is 1.41 m. The maximum storage capacity of the Shesh Netra lake and Badrish lake comes out to be 8448 m^3 and 4493 m^3 respectively. The surface area of Shesh Netra lake is 4676 m^2 while that of Badrish lake is 3177 m^2.

iii) Depth-area-capacity curves have been developed for both the lakes. These curves provide the surface area and capacities of the lakes at different water levels in the lakes.