Lake Bathymetry, Morphometry and Hydrochemistry of Gosaikunda and Associated Lake

Basudev Neupane[1*], Sudeep Thakuri[1,2], Nabin Gurung[1], Aavash Aryal[3], Bidhan Bhandari[3], & Kribina Pathak[1]

[1] *Central Department of Environmental Science, Tribhuvan University, Kathmandu*

[2] *Faculty of Science and Technology, Mid-West University, Surkhet*

[3] *Nepal Mountain Academy, Kathmandu*

**Correspondence: bashudevneupane@gmail.com*

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Abstract

Gosaikunda and Bhairabkunda are two largest lakes among dozens of lakes in the upper Ghattekhola watershed of Trisuli River in Nepal. Although being important high-altitude Ramsar site from Nepal, a detailed inventory that includes essential information on their hydrological, physical, chemical, and biological characteristics and human interactions are missing. We conducted an inventory of the lakes in the watershed in the previous study and in this study, we present the lake bathymetry, morphometric characteristics and hydrochemistry following recent methodologies. The Gosaikunda and Bhairbakunda have the maximum depth of 26.5 m and 59.1 m with area of 13.3 and 16 ha, respectively. The study supports to establish a reference site for exploring scientific evidence on the impacts of anthropogenic and climate change on lake hydrological systems in the future.

Keywords: *Himalaya, alpine lake, wetland, bathymetric model, lake morphology*

Introduction

Using the bathymetric map, it is possible to determine the lake dimensions, area, maximum depth, calculate volume, and mean depth (Dumpis et al., 2020). Bathymetric maps are widely used to study the lake by determining the exact shoreline of the water body based on the former water level at the time of the depth measurements. Any lake's water level fluctuations are caused by processes such as atmospheric circulation, changes in solar radiation, which determine the thermal and ice regime of the lake, as well as precipitation (Aigars et al., 2018; Dumpis al., 2020).

Lake morphology is attributed as a key factor for the understanding of lacustrine structure and function. Lake morphology is quantified and measured with morphometric metrics that are descriptors of the form and size of lake basins (Schiefer & Klinkenberg, 2004). This analysis provides pivotal knowledge in support of inferences to lake management including Lake Genesis and physical perspective (Hollister, Milstead, & Urrutia, 2011). Geographical information systems are becoming useful tool for processing and analysing morphometric metrics of areas and volumes (Hollister et al., 2010). Morphometric parameters for lakes are of great importance. They contribute to explaining many research issues, such as water balance, water exchange rate, or rate of shallowing (Choiński & Strzelczak, 2011).

In the world, the study of lakes in terms of physical, chemical, and biological characteristics has been developing rapidly since the beginning of the 20th century (Dumpis, Lagzdins, & Sics, 2021). The historical outline of bathymetric measurements is intriguing. In 1815 AD, the scientist Staszic did not have a boat at the site and tried to measure the lake depth standing at the shore and was repeatedly throwing a lead ball to determine the depth (Choiński & Strzelczak, 2011). The modern technologies provide an opportunity to collect water depth data much more efficiently than in the past. There are also many opportunities to process these data to develop bathymetric maps and perform various calculations in the computer environment (Dumpis et al., 2020).

In Nepal, few studies are carried out for the bathymetric survey of lakes. Tsho Rolpa, Imja, Thulagi, Lower-Barun glacial lakes were studied as these lakes were identified as potentially dangerous. In the early 1990, bathymetric studies were carried out for Lower-Barun, the Imja, Tsho Rolpa, and Thulagi Glacier lake (Ghimire, 2004). The DHM carried out a bathymatric survey of Phoksundo lake, assuming the deepest lake, using the echo-sounder instrument (DHM, 2019).

A study of the inorganic components in water can give information on several subjects (Bhatta et al., 2020). The trace metal concentration in lake waters is controlled mainly by the hydrochemistry of the basin, which in turn is controlled by processes like precipitation, rock weathering, and evapotranspiration (Meybeck, 1987). The high-altitude Himalayan lakes are characterized by the presence of glacial silt, low Secchi values, low conductivity, and neutral pH whereas the most dominant cation and anion in high altitude lakes are Calcium (Ca) and Bicarbonate (HCO_3), respectively with few exceptions (Ghimire, 2004).

The lakes are sensitive indicator to climate change (Tan et al., 2017). Elevation-dependent warming can accelerate the rate of change in mountain ecosystems, cryospheric systems, hydrological regimes, and biodiversity (Thakuri et al., 2021). Climate change impacts on Himalayan wetlands can be considered at two levels: first, the impacts of forcing factors and their interactions with wetland processes and, second, the overall impacts on different kinds of ecosystem goods and services. Impacts range from the direct effects of increasing concentrations of CO_2 and the resultant rise in temperature to the indirect effects caused by alterations in the hydrology caused by melting glaciers and ice cover and changes in precipitation regimes (Gopal et al., 2016).

High altitudes wetlands are regarded as "any wetland types that are found above the elevation of 3,000 masl" (Bhandari, 2005) and Gosaikunda is one of them. The remote location, pristine state, connection with local culture, and habitat providing function for various life forms make these wetlands valuable. The health of these wetlands is of significant significance to a vast population not just upstream, but to the area downstream as well (Upadhaya, Chalise, & Paudel, 2009). Wetlands are one of the most poorly understood ecosystems, despite recognizing the importance of their goods and services. A list or map of their distribution and size is of no help in assessing their functions or ecosystem services and, consequently, the likely impacts of climate change. There is an urgent need for detailed inventories that include essential information on their hydrological, physical, chemical, and biological characteristics and human interactions (use and impacts) with each system (Gopal et al., 2016).

Study area

Gosaikunda and associated lakes are situated in the Ghattekhola watershed in the upper part of the Trisuli River Basin (5,762 km^2) of Nepal. The study area, the Ghattekhola watershed, covers 59.2 km^2 in the Tirsuli River system (Figure 1). The watershed extends from 1,274 to 4,993 m. A total of 22 lakes, with a total surface area of 80 ha in 2020, were identified within the watershed, ranging from 0.2 to 15.5 ha in size and an estimated 9,491,000 m^3 of water volume available on the surface as the stagnant water body in the watershed (Thakuri et al., 2021).

Gosaikunda and associated lakes serve as sources of water for the Trishuli River. The lakes are in Ward Number 5 of Gosaikunda Rural Municipality in the Rasuwa district of Bagmati Province. It is located about 30 km north (aerial distance) of Kathmandu valley and is about one and a half days walk from Dhunche; headquarters of Rasuwa district. Geographically, the freshwater wetland lies in a U-shaped valley above 4000 m on the lap of hill Gosai, from where it burrows its name (Upadhaya et al., 2009).

Gosainkunda and associated lake areas, one of the country's holiest and sacred lands, is an alpine freshwater oligotrophic lake series formed by glacial water and remains frozen for at least six months of the year (Lacoul & Freedman, 2005; Shrestha et al., 2020). Langtang is a place of pilgrimage for both Hindus and Buddhists. Every year more than 10,000 people visit Langtang to take a holy bath at Gosainkunda in average (Koju & Chalise, 2012). The number of pilgrims has increased from nearly 5,000 in 1999 (Basnyat et al., 2000) to more than 20,000 during the 7 days around the *Janai Purnima* festival in August 2017 (Bhandari & Koirala, 2017).

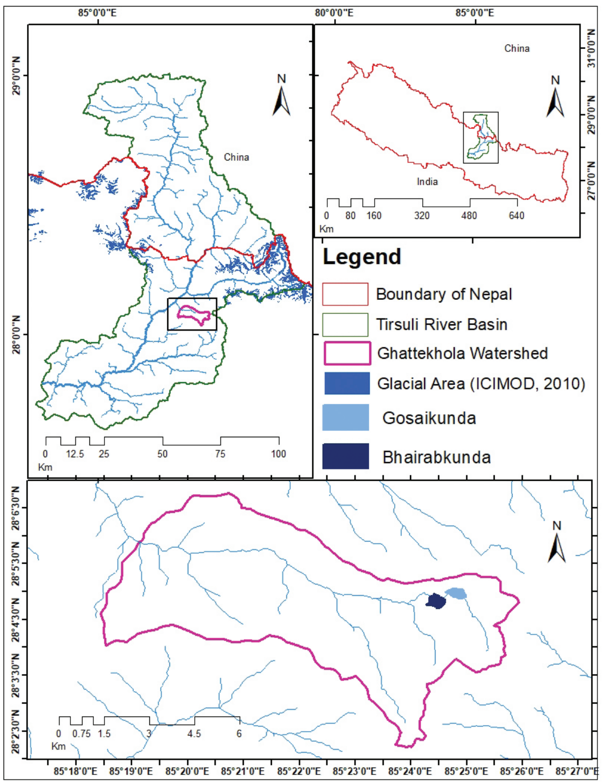

Figure 1: *Study area showing the Gosaikunda and Bhairabkunda lake in Ghattekhola watershed of Trisuli River basin*

Every year on the *Janai Purnima* and Dashain festival, thousands of national and foreign pilgrims climb up the hill and take a bath in this holy Kunda (lake). Socio-cultural significance Hindu mythology mentions Gosaikunda as Hindu deities like the Lord Shiva and the Goddess Gauri. Hindu scriptures like the Bhagawat Gita and the Bishnu Puran and Hindu epics like the Rāmāyana and the Mahābhārata mention about the *Samundra Manthan* (sea exploring), which is directly related to the origin of Gosaikunda. It is believed that the lake originated when the Trishul (trident) thrown by the Shivā pierced the wall, and the Gangajal (supposedly holy water) filled the pond. The sacred water of Gosaikunda is used during the *Gangadashahara* and the *Janai Purnima* by thousands of people visiting the place from Nepal and India to celebrate the festival. People believe that one's ancestors can go to heaven after bathing in the lakes. The area is culturally rich, with Tamang as a major ethnic group (Upadhaya et al., 2009). The site is equally famous for Yak cheese. About 25-30% of the tourist visiting Langtang National Park visit the Gosaikunda area.

Data and methods

Image analysis

The Google Earth Image (GEI) and Sentinel image of December 11, 2020 (Scene ID: S2A_MSIL1C_20201211T050211) were the primary data source for preparing an inventory of the lakes. Initially, lakes were identified and digitized in the GEI and exported as a KML file. We used ArcGIS10.7 for further processing of the data. We used the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM; METI and NASA) of 30 m resolution to extract the river and watershed boundary.

We compared GEI lake inventory with the Sentinel satellite image and Nepal's official topographic map (1992) to validate the lake inventory. Also, we compared the dimensions (area, perimeter) of selected large lakes. The volume of each lake was estimated using the empirical equation based on the surface area of the lake. We used the equation successfully applied by Khanal et al. (2015) in the Poiqu/Bhote Koshi/Sun Koshi River basin, a similar geographic and climatic region located close to the current study site.

This equation was proposed based on the trend line derived from the area and volume of high-altitude lakes in the Hindu-Kush-Himalaya region. The equation is represented as,

Volume of the lake (m^3) = 0.0578*A1.4683

Where A = surface area of the lake.

Bathymetric survey

For the bathymetry survey Humminbird Depth Sounder-HDR 650, GPS Meter (GPSMAP® 64s), and Rafting boat were used similar to the study in Lower-Barun Glacial Lake (Gurung, et al., 2021). In October 2021, the survey was conducted along transverse and longitudinal transect lines as per the designed protocol.

The HDR 650 Digital Depth Sounder uses sonar to determine depth directly below the transducer. Sonar technology is based on sound waves. The HDR 650 Digital Depth Sounder consists of the HDR 650 sonar unit and the transducer. The sonar unit contains the transmitter and receiver and the user controls and displays. The transducer is mounted beneath the water surface and converts electrical energy from the transmitter into mechanical pulses or sound waves. The transducer also receives the reflected sound waves and converts them back into electrical signals for display on the sonar unit. Sonar is very fast. A sound wave can travel from the surface to a depth of 70 m and back again in less than 1/4 of a second.

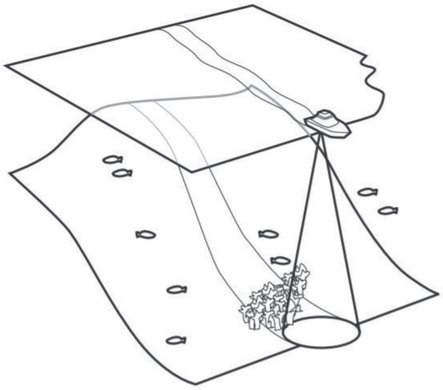

Figure 2: *Principle of Depth Sounder. Image by: Huminbird*

The time taken by the waves to travel to and from the seabed is measured, and the formula can determine depth:

Distance=Velocity x Time/2

The frequency of the transducer is a crucial factor in the depth of your range but also the level of information provided. Typically, the lower the frequency, the more practical for deeper waters (something like a 50 kHz wave will penetrate further whereas 200 kHz is more suitable for shallow waters); however, the benefit of the higher frequency is that the detail of the imaging returned is much greater than that of the lower ranges.

Bathymetric models were created within ArcGIS 10.7 using natural neighbor interpolation (Haritashya et al., 2018; Thompson et al., 2016), and lake volume were calculated. Bathymetric modeling requires an outline with zero depth. The outline zero-depth data were generated lake extents using multispectral satellite imagery.

The morphometric parameters are calculated as of following (Håkanson, 2004) :

$$Mean\ Width\ (m) = A/Lmax$$

where A is area in Square meter and Lmax is maximum length in meter

$$Mean\ Depth\ \bar{D} = V/A$$

where, V is Volume in cubic meter and A is area in square meter.

$$Depth\ Ratio = \frac{Mean\ Depth\ (\bar{D})}{Maximum\ Depth}$$

Physicochemical analysis

We measured pH, Dissolved Oxygen (DO), Turbidity, Water Temperature, Total Dissolved Solids (TDS), and Electrical conductivity using automatic measuring machines during a field visit in October 2021.

Turbidity was measured by the "2100Q Portable Turbidimeter" manufactured by HATCH. Turbidity measurement involves using a light beam with defined characteristics to determine the semi-quantitative presence of particulate material present in the water or other fluid sample. The light beam is referred to as the incident light beam. The material in the water causes the incident light beam to scatter, and this scattered light is detected and quantified relative to a traceable calibration standard. The higher the quantity of the particulate material contained in a sample, the greater the scattering of the incident light beam and the higher the resulting turbidity.

EC59 Pocket-size Conductivity / TDS / Temperature Meter with the replaceable electrode (MW803) of Milwaukee instruments were used to measure the electrical conductivity, TDS, and water temperature of the water samples collected from different locations. The machine shows readings in an extended range from 0.00 to 14.00 pH and 0 to 3999 µS/cm, 0 to 2000 ppm TDS, and simultaneously indicates temperature from 0.0 to 50.0°C.

Milwaukee pH55 Martini Pocket pH Meter was used to measure the pH of the water samples collected from different locations. This is an automatic, 1 point machine with 2 sets of memorized buffers (pH 4.01, 7.01, 10.01 or 4.01, 6.86, 9.18) with the accuracy of ±0.1 pH.

Results and discussion

Bathymetric maps

The bathymetric survey was carried out using the established methodology with the help of potable depth sounder and Global Positioning System (GPS) to generate XYZ hydrographic data points (Yesuf et al., 2012). The data obtained from the field was processed in ArcMap 10.7 and presented in figure 3. The maximum depth of Gosaikunda is 87 ft and the maximum depth of the Bhairabkunda is 194 ft.

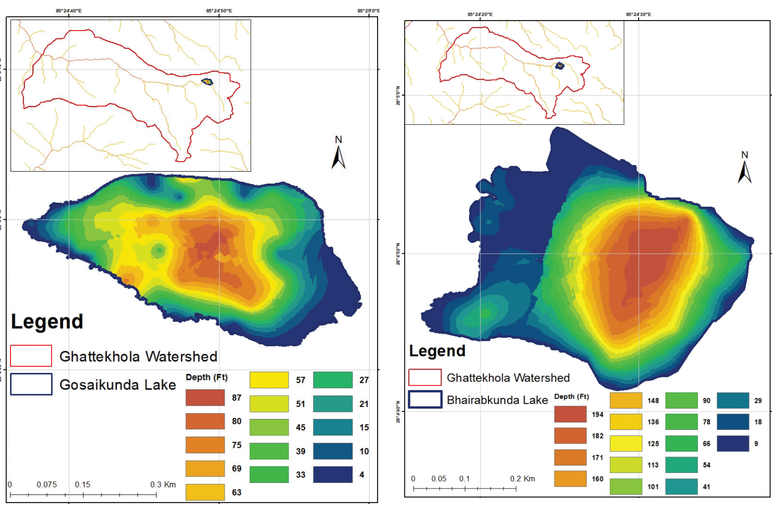

Figure 3: *BathymtericmMaps of Gosaikunda (Left) and Bhairabkunda (Right)*

The bathymetric map of the lake shows the distribution of the water depth of the lake, its variability, and the terrain. Water depths are fundamental in several physical and biological processes occurring in lakes. The lake's depth influences its water quality economic exploitation potential (fishing, recreation, shipping, water abstraction for agricultural use, drinking) (Jānis Dumpis et al., 2020). Since, the bathymetric map is visually clear for interpretation, it could serve as important tool for planers and decision makers to implement the effective lake management plan.

Figure 4: *Gosaikunda Lake and associated Bhairbakunda Lake in Ghattekhola watershed (photo taken during the field visit in October 2021)*

Morphometric characteristics

Lake Morphometric parameters provide helpful information to assess the lake residence time, life expectancy, sedimentation rate, water balance, and sustainable abstraction of water and derive stage volume/area curves (Yesuf et al., 2012).

Table 1: Morphometric values of Gosaikunda and associate Bhairbkunda Lake in Ghattekhola

Morphometric Parameter	Unit	Morphometric value (Gosaikunda)	Morphometric value (Bhairabkunda)
Maximum width	M	635	592
Maximum effective width	M	629	592
Mean Width	M	212	278
Maximum Depth	M	27	59
Mean Depth	M	14	15
Depth Ratio	M	0.51	0.25
Direction of major axis	-	NW-SE	SE-NW
Perimeter	M	2200	2054
Total Lake area	Ha	13.3	16.5
Volume	1000 m^3	180	2416

The variability of the morphometric data obtained does not unambiguously indicate the evolution of the lake in terms of swallowing. This situation is probably caused by the different times of measurements (Choiński & Strzelczak, 2011).

Physio chemistry of surface water

During a field visit in October 2020, water samples were collected from 3 different parts of each lake. The physicochemical parameter of the two lakes of the Gosaikunda series was measured and shown in Table 2. .

Table 2: Physicochemical Parameter of Gosaikunda Lake (On October 9, 2021)

	Site 1 (Middle Part)	Site 2 (Near Temple)	Site 3 (Inlet)
Temperature (°C)	12.2	12.3	12.2
Turbidity (NTU)	6.1	6.1	6.1
Electrical Conductivity (µs/cm)	7	7	7
Total Dissolved Solid (TDS) (mg/L)	4	5	4
pH	8.1	8.4	8.2

Table 3: Physicochemical parameters of Bhairbkunda Lake (On October 10, 2021)

	Site 1 (Middle Part)	Site 2 (Outlet)	Site 3 (Inlet)
Temperature (°C)	11.8	11.7	10.9
Turbidity (NTU)	7.9	7.9	7
Electrical Conductivity (µs/cm)	15	11	7
Total Dissolved Solid (TDS) (mg/L)	7	6	8
pH	8.3	8.2	8.2

Different lake watershed and lake water processes, like sedimentation, deposition, re-suspension, and flushing, determine the pollution level. Different studies considered the physicochemical analysis of the Gosainkunda lake water (Raut et al., 2012; Bhatta et al., 2014; Sharma et al., 2015; Rupakheti et al., 2017). The Ca^{+2} (64%) is the dominant cation, and Cl- (49%) is the dominant anion of the lake water. The order of cation concentrations in the lake was $Ca^{+2} > Mg^{2+} > Na^{+} > K^{+}$ (Raut et al., 2012). In contrast, Begnas lake, located in the lower urbanized area, had slightly higher concentrations of Na^{+} than that of Mg^{2+} (Khadka & Ramanathan, 2012). Higher concentrations of major solutes appear at the northern lakeshore near the trail due to human and livestock influence (Bhatt et al., 2014).

Based on the water quality index (WQI), high-altitude lakes (e.g., Lake Gosainkunda) were found to have better water quality than the urban lakes (e.g., Lake Phewa). WQI suggests an excellent water quality of the Gosainkunda lake due to its remoteness and less direct contact from human activities (Rupakheti et al., 2017). The high-altitude lakes help detect anthropogenic disturbance to serve as an indicator. A previous study based on water chemical constituents' analysis shows the increased anthropogenic disturbance in the lake. The Mercury concentration is reported higher in the Gosainkunda lake than low altitude Phewa lake, possibly due to long-range transport of pollutants and partially contributing from the natural geological sources. Further, the trace element constituents of water such as Ni, Cu, Zn, Cd, and Pb in the water contributed to anthropogenic sources (Sharma et al., 2015).

Though the high-altitude lakes have better water quality than the urban lakes located in the southern part of the country, the evidence shows increasing local and long-range transport and deposition of the pollutants in the lake water. Increasing human activities in and around the lake, long-range transport of contaminants, and changing environment in the area demand the lake's conservation. Human uses include grazing during summers, and there are also hotels with campgrounds for trekking groups and pilgrims. Solid waste pollution due to a large-scale gathering of humans during the festive seasons and the long-range transport and deposition of the pollutants on waters have been threats to the site.

Disappearance of small lakes in the Ghattekhola watershed

The Gosainkunda lake and its surroundings were expected to have 108 lakes. Still, images of different years from 2015 to 2020 have demonstrated that some of the lakes have already disappeared/dried, some have become ephemeral in the region (Thakuri et al., 2021).

We collected photos of the seasonal and disappearing lakes during a field visit in October 2021 from the study area (Figure 5).

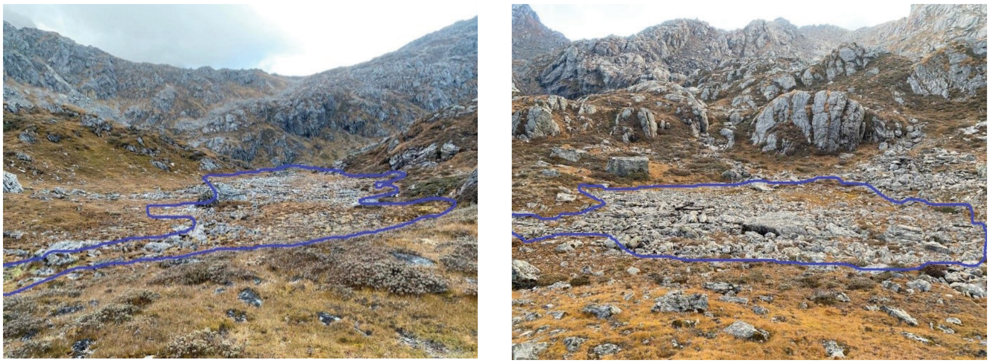

Figure 5: *Disappearing Lakes in the upper part of Ghattekhola watershed (Photos from field visit in October, 2021)*

The high mountain areas are more rapidly warming than Nepal's southern lowlands. In areas above 1000 m elevation of Nepal, the maximum temperature has increased by 0.072°C year. In the areas below 1000 m, the maximum temperature has risen only by 0.028°C year in the last four decades (1976-2015). The warming is more severe than nationwide warming because the maximum temperature of Nepal increased by 0.45°C/decade and the minimum temperature by 0.09°C/decade from 1976-2015 (Thakuri et al., 2019). Further, the diurnal air temperature range has increased by 0.034°C year in the same period. The average rate of temperature change in Nepal is higher than in other regions due to the elevation gradient of Nepal.

Mountain environments, mountain hydrology, and mountain inhabitants' livelihood have been affected by climate change in a direct and indirect manner (Bhadra et al., 2020). The impact of climate change is different in the glacial lake and high mountain lakes. Elevation-dependent warming can accelerate the rate of change in mountain ecosystems, cryosphere systems, hydrological regimes, and biodiversity. Rising temperature causes fluctuation in the rainfall snow cover in the high mountains, which are principal water sources for the downstream population and ecosystems Salerno et al. (2016). The same study confirmed that glacial melting and precipitation trends could be detected by surface area changes of the Himalayan lakes. Thus, the lakes are a good indicator of precipitation and temperature change. Salerno et al. (2014) demonstrated that the alpine ponds shift upwards as average temperatures increase. Increasing temperature enhances the glacier and permanent snowmelt process and creates a favorable condition for the formation of the lakes in high altitudes. Increased evaporation/precipitation ratio associated with climate warming can be the possible cause of the lakes' disappearance (Salerno et al., 2015).

Landslide, erosion, and lake depth

During the field visit in October 2021, we observed numerous landslides and fast erosion in the area (Figure 5). In the North-West part of the Gosaikunda, few small landslides and traces of high erosion have been observed.

Since, the high mountain area is fragile, the erosion and landslide are common but the accelerated erosion and bigger landslides are threat to the high mountain Ramsar site.

Figure 6: *Small landslides and erosion process in North-West part of Gosaikunda Lake (Photo from field visit of October, 2021)*

Conclusion

The outcome of the depth sounder survey provides a satisfactory description of the bathymetry of Gosaikunda and associate lake, and such information should be of value to subsequent limnological and ecosystem research (Hickley et al., 2003). The upper part of the Trishuli River basin in Nepal, i.e., the Ghattekhola watershed, has 22 lakes, extending from 1,274 to 4,993 m elevation and covering 80 ha. The water bodies (lakes) are drying in the region. Some lakes have already disappeared from the territory, and some are evolving as temporary water bodies. The depth of the two largest lakes of the Gosakinda Lake series has been measured with accepted scientific tools and found that the maximum depth of Bhairabkunda Lake (194 ft.) is greater than the Gosaikunda lake (87 ft.). The reported chemical constituents could have resulted from the anthropogenic activities in and around the lake, chemical components of the source area, and possibly is evidence of the long-range transport of pollutants.

Since this is the first bathymetric survey with established scientific methodologies, this study supports establishing reference sites for exploring scientific evidence on the impacts of anthropogenic and climate change on lake hydrological systems (Thakuri et al., 2021) in the future.

The number of visitors is increasing annually, consenting to the cultural importance of the region. Due to increasing human pressure in and around the lake, long-range transport of pollutants, and issue of the climate changes in the area are possibly threatening the existence of the lakes and appealing for their conservation needs.

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Author contribution

BN & ST – Conceptualization and Methodology, NG, AA, BB – Field works, KP – Draft Manuscript writing, BN, ST, KP: Review and finalization of the manuscript

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