First Results on Lake Bathymetry of Panch-Pokhari Complex, Langtang Region, Central Nepal

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DOI: http://doi.org/10.3126/jtha.v6i1.67395

Abstract

The Panch-Pokhari complex, a group of five lakes, is one of the high-altitude wetlands of Nepal that has received very less attention. While these lakes hold significant religious importance, they are less known from a morpho-ecological perspective. The objective of this study is to develop a bathymetry model of the lakes through afield survey and geospatial analysis. This study generated new insights into the limnological and morphometric features of the five lakes through detailed mapping and profiling. The bathymetric analyses revealed diverse basin morphometry among the lakes, with Lake 1 being the largest, in term of its depth of 12.1 m and water volume of 208,352 m^3. In contrast, Lake 5 was the smallest and the shallowest with a depth of 1.4 m and volume of 1,921 m^3. This study establishes a new baseline to advance scientific understanding of the Panch-Pokhari complex. Further, integrated research combining limnological, ecological, and social aspects is recommended to support evidence-based planning for the conservation of these vital Himalayan wetlands.

Keywords: bathymetric, high-altitude lake, morphometry, Panch-Pokhari, water depth

Introduction

Freshwater wetlands are the most productive ecosystems, providing a wide range of ecological benefits to people. Further, the wetlands have a unique role in ecosystem support by controlling the water cycle (Mitsch et al., 2015). By holding huge volumes of water and releasing it during shortages, proper lake operation can reduce the impact of floods and droughts. Lakes also recharge groundwater, acts as sink by improving the water quality of downstream watercourses, and supports the area's biodiversity and ecosystem (Kumar & Lamsal, 2016). With this insight, the Convention on Biological Diversity of 1992 gave wetlands protection a high priority since the benefits they provide directly contribute to people's lives and economy (CBD, 1992). Lake dynamics are the indicator of paleoenvironment. In mountain regions, lake development and changes over time are an obvious and easily measurable indication of human activities and climate change consequences (Thakuri et al., 2021a; 2021b). A lake is closely related to the atmosphere, biology, soil and other factors, and it is very sensitive to changes in the climate and environmental system (Li et al., 2015; Sharma et al., 2012).

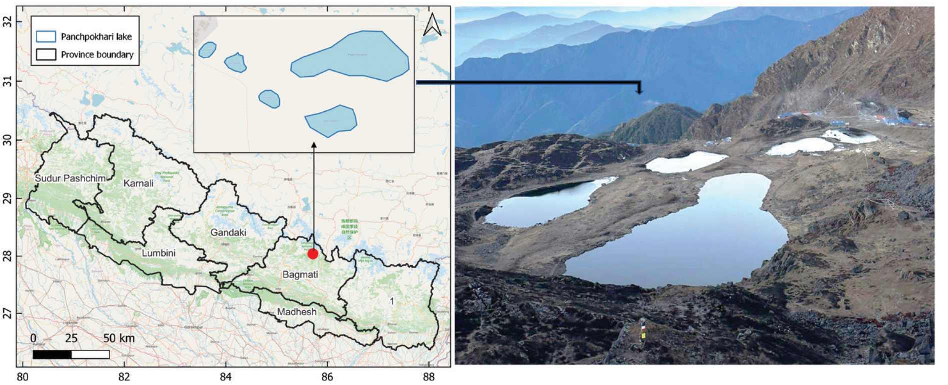
Studies show that the climate factors are more important for lake changes, while human activities such as the area of cultivated land and the built-up area had obvious effects on the lakes (Jing et al., 2018). In 2017, there were 1,541 lakes larger than 0.36 hectares located above 3,000 meters in elevation, a significant increase from 606 lakes in 1977 (Khadka et al., 2018). Attempts were made to list some of these lakes, including Panch-Pokhari, in Ramsar site of Nepal. Yet, there is no detailed geomorphological, socio-economic, biological, and physico-chemical study of the lake and its periphery watershed. Therefore, it would add value to the process if the lake's geomorphological characteristics can be known. Thus, the aim of this study is to develop a lake bathymetry of Panch-Pokhari of Nepal.

Study site

Panch-Pokhari, one of the high-altitude lakes, is located in Sindhupalchok district in Bagmati Province of Nepal. It is an association of five Hindu holy lakes (Figure 1). The five lakes of Panch-Pokhari are located at an elevation from 4,055 to 4,068 m above sea level. The lake is popular among the Hindu and Buddhist pilgrims. The Panch-Pokhari is considered one of nature's most beautiful, unspoiled, and well-kept secrets with mysterious landscapes. This region is characterized by the magnificent mountains, exceptionally unspoiled natural beauty, amazing wetland features, and diverse flora and wildlife. This lake is one of the major attractions of Langtang National Park as well. A range of peaks known as the Jugal Himal, which includes the peaks of Dorje Lhakpa (6,966 m), Madiya (6,257 m), and Phurbi Chhyachu (6,637 m), is located to the north of the Kathmandu valley along the trekking route of Panch-Pokhari. Despite being located close to Kathmandu, this area is rarely visited by people, except as pilgrims.

Figure 1

Location map of study area



Note: A map of Nepal showing the location of Panch-Pokhari complex (upper) and a horizontal photo of the lake complex

Data source

This study uses the data collected from the field survey and remote sensing. To develop a bathymetric model of the lakes, we used data obtained by depth soundings from systematic transects across each lake using echo-sounders/sonar, GPS mappings to delineate lake boundaries, topographic maps and digital elevation model (DEM) for the catchment area delineation, satellite imagery for analysing lake morphology. The Google Earth Imagery, Sentinel 2 and ASTER GDEM (30 m) were used for obtaining the basin characteristics and analysing lake surface area changes.

Field activities

The field study was conducted from October 31 to November 6, 2023. During the field survey, bathymetric data was collected using Depth sounder and GPS. The morphological characteristics of lakeshore (including mountain slope, inlets, outlets, land use) were collected. Line transects were established along the surface of the lakes to measure the bathymetry as demonstrated in Figure 2.

Figure 2

Bathymetric survey plan (left) and water depth measurement during the field (right)

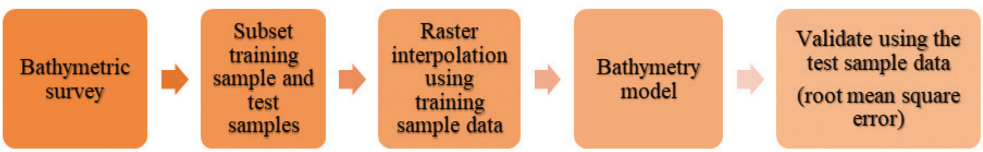
A depth sounder (HDR 650 Hummingbird®) and Garmin GPS 64s were employed for the bathymetric survey. The depth sounder had the capacity to measure depths upto 180 m. Prior to its use, the depth sounder underwent calibration to address any discrepancies in measurement. The Garmin GPS 64s had a positional accuracy of 3 m. Similar method was applied by Thakuri et al. (2021a) who also deployed depth sounder and GPS to measure the depth across different regions in Rara and Begnas lake.

Data analysis

The depth data collected for each lake water column was used to generate bathymetric maps and lake terrain elevation models. Further, the area and volume of the lakes was computed. Altogether 459 depth points were collected. The depth data collected were divided into training samples (75%) and test samples (25%). The Inverse Distance Weighting (IDW) interpolation technique was used (Diaconu et al., 2019) with power 2 and number of points (n=12) using the training samples to generate the bathymetric model (Figure 3).

Figure 3

Process of bathymetry modelling



The IDW interpolation is a suitable technique for generating continuous prediction surfaces from a small number of point samples, like lake depth soundings. It assumes that points closer together are more similar than those farther apart. The influence of a known data point on the prediction surface diminishes with increasing distance. The interpolated values are weighted averages of the sampled points, with closer points given higher weights. The weighting power parameter controls how steeply weights decline with distance. The IDW interpolation is given by,

$$z_p = \frac{\sum_{i=1}^{n} \left(\frac{z_i}{d_i^p}\right)}{\sum_{i=1}^{n} \left(\frac{1}{d_i^p}\right)}$$

Where, Z_p = interpolated values for the given power, n= number of points, p = power, d_i = distance between the points

The validation of the model was performed using Root Mean Square Error (RMSE) using the test sample and the extracted modelled value for the sites of the test samples (Yang et al., 2022a, 2022b).

The result was plotted in the ArcGIS software and presented through maps and charts.

Results and discussion

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}$$

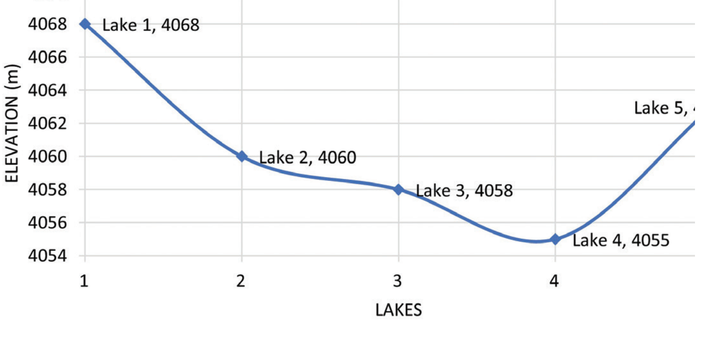
$\hat{y}_1, \hat{y}_2, \ldots, \hat{y}_n$ are predicted values
$y_1, y_2, \ldots, y_n$ are observed values
n is the number of observations

Lake characteristics and bathymetric modelling

The Panch-Pokhari complex located in the Sindhupalchok district is characterized by its unique setting of five lakes situated at elevations between 4049 m and 4063 m (Figure 4). The lakes fill deep basins carved out by glacial processes and exhibit diverse morphometry, with areas ranging from 0.14 ha (the smallest Lake 5) to over 2.6 ha (the largest Lake 1). The water depth extends to over 12.10 m in the deepest sections of Lake 1 (Table 1). The minimum depth was observed for Lake 3 with only 0.87 m. The steep surrounding hill slopes are forested while the lakeshores have some marshy stretches. The lakes are recharged by rains and snow melt, small inflows, and groundwater springs.

Figure 4

Elevation profile of the Panch-Pokhari complex



The total area of the lake accounts for 4.013 ha, Lake 1 having a maximum area and Lake 5 having a minimum area. The average depth also shows a similar pattern with Lake 1 having maximum depth (7.7 m) and Lake 5 having minimum depth (1.3 m). The detailed characteristics of the lake complex is given in Table 1.

Table 1

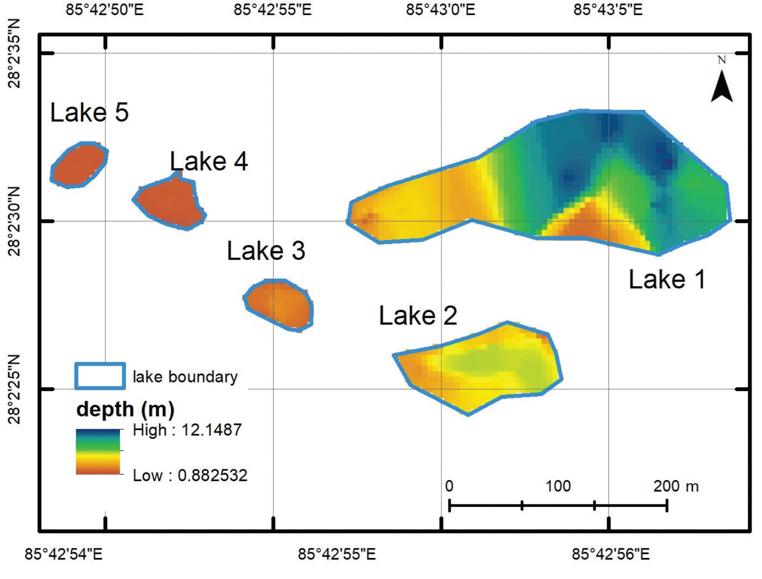
Characteristics of the lake complex

Lake	Area (m^2)	Min depth (m)	Max depth (m)	Range (m)	Average depth (m)	SD	Volume of water (m^3)	Maximum width (m)
Lake 1	26887	1.19	12.10	10.92	7.75	3.03	208353	318
Lake 2	7981	1.95	6.10	4.16	4.90	0.96	39061	150
Lake 3	19530	1.36	2.80	1.44	2.21	0.36	4314	59
Lake 4	1897	0.87	1.50	0.62	1.37	0.10	2596	68
Lake 5	1414	1.24	1.41	0.17	1.36	0.07	1921	50
Total	**40130**						**256246**	

The high-resolution bathymetric maps were generated for each of the Panch-Pokhari complexes (Figure 5). The map illustrates the distinct morphometry and depth contours of each water body (Figure 6).

Figure 5

Modelled depth distribution of Panch-Pokhari complex



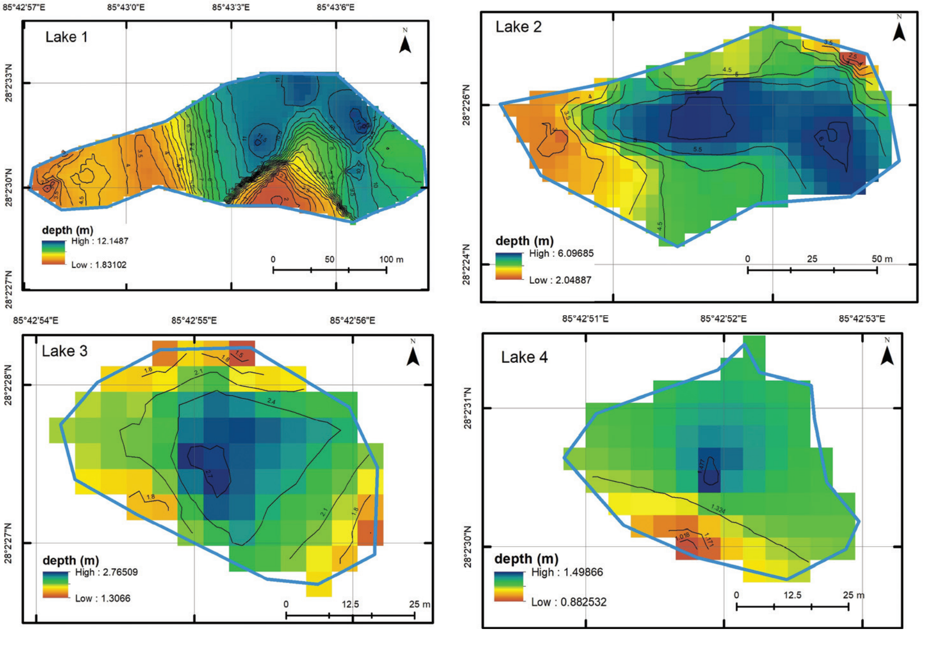
The largest lake, Lake 1, the deepest in the complex spans over 318m lengthwise and has an irregular oval shape, with contours showing a relatively gradual slope along the northern and eastern shallow littoral shelf which then drops off more steeply along the southern basin to reach maximum depth of over 12.1 m. Several isolated depression zones between 11.0 and 11.5 m deep are also scattered across the central sector of Lake 1 (Figure 6a). The minimum depth of 1.2 m was observed on the south and southwest aspect of the lake. The average depth was calculated to be 7.74 m. The volume of water in the lake was estimated to be 208,352.97 m^3. Lake 2 shows a linear elongated form orientated east-west, with steeply dipping margins plunging to over 6.1 m depth. The minimum depth of Lake 2 is 1.9 m. The bathymetry delineates an underwater ridgeline that runs longitudinally, dividing the southern part of Lake at 2.1 m. The maximum length of Lake 2 is 149.7 m (Figure 6b). The volume of water in the lake was estimated to be 39,061 m^3.

Lake 3 exhibits an oval basin morphology, with a rather consistent slope descending radially from the near shore lake margins to the flat basin floor lying with the depth range of 1.3- 2.7 m. The distinct shelves and depressions reflecting the underlying bedrock topography are captured in the detailed bathymetric renderings (Figure 6c). The lake extends to a length of 59.24 m. The lake has an average depth of 2.21 m and contains an estimated 4,314.4 m^3 of water in the lake (Figure 6c). Lake 4 manifests slight round basin morphology. Analysis of depth soundings across the lake surface showed the depth range of 0.8 – 1.5 m. The mean depth across the entire lake area was determined to be 1.36 m, indicating the presence of a shallow water pool. The total estimated water volume contained in Lake 4 was calculated to be 2,596.4 m^3. The lake occupies a surface area of 1896.8 m^2 according to the bathymetric model (Figure 6d). Lake 5 is the smallest of all, having an area of 1413.75 m^2. It is also the smallest in terms of the width (50.21 m). The lake is very shallow with a depth range of only 0.172 m. The maximum depth was predicted to be 1.41 m and a mean depth of 1.35 m. The volume of water in the lake was estimated to be 1921 m^3.

The RMSE for the model was determined to be 0.32 m indicating the acceptability of the model. Several other studies (Yang et al., 2022b; Wang et al., 2023) have reported even higher RMSE for the Bathymetry Model.

Figure 6

Bathymetry model for the four lakes of the Panck Pokhari complex



The high-resolution maps and depth profiles provide new insights into the physiographic factors and processes controlling the morphometry of the Panch-Pokhari. The location of rock basins, shelves, and ridges reflected in the bathymetry corresponds well with the underlying bedrock geological structure and faults affecting the lake complex. The deeper areas manifest where bedrock depressions have subsided, while shallower zones correlate to in-filled sediments. The slope morphometry relates to each lake's development history within the glaciated valleys. Lake 1's gentle littoral zone reflects substantial alluvial and deltaic sediment deposits, while Lake 2's steeply plunging margins conform more to the original glacial over-deepened basin morphology. The bathymetric data enhances understanding of the hydrology, water circulation and ecological conditions of the lakes. There is high biodiversity of phytoplankton, zooplankton, fishes, birds and other biota, though populations are threatened by pollution and habitat loss (Krstić et al., 2012; Raut et al., 2017). The Panch-Pokhari is culturally significant for local religious practices and recreationally valued for its pristine beauty, attracting many hikers, and pilgrims. Conservation initiatives aim to balance ecological protection with low-impact tourism at this important wetland complex.

This study generated new insights into the limnological and morphometric features of the five lakes through detailed mapping and profiling. The bathymetric analyses revealed diverse basin morphometry among the lakes, with Lake 1 being the largest, deepest and most voluminous with a maximum depth of 12.1 m and volume of 208,352 m^3. In contrast, Lake 5 was the smallest and shallowest with a depth of only 1.4 m and volume of 1,921 m^3. Compared to other lakes of similar altitude, the Panch-Pokhari complex has a shallower depth and smaller area. The Gosaikunda and Bhairbakunda that lie in similar altitude have the maximum depth of 26.5 m and 59.1 m with area of 13.3 and 16 ha, respectively (Neupane et al., 2022).

The depth of Lake 1 of the Panch-Pokhari is similar to the depth of the Begnas Tal. The Begnas Lake had a maximum depth of 12.5 m, spanning an area of approximately 2.98 km^2, but the Rara Lake's dimensions were too high, with a depth reaching 169 m, and covering an area of 10.52 km^2 (Thakuri et al., 2021a). The bathymetric analysis of lakes in Ramroshan, Achham showed that Jingale Lake (44 m), Batula (15 m) had higher depth than the Panch-Pokhari Lake, but Mathillo Dhaune (9.5 m) had depth similar to that of Lake 2 in Panch-Pokhari (Chalaune et al., 2020). The varying slopes, shelves and depressions reflected the underlying bedrock structure shaped by lacustrine processes. Sedimentation patterns also differ from the lake's developmental history (Watson et al., 2019).

These quantifications of lake morphometry provide critical physical data to improve hydrological and habitat modeling for conservation and management of this high-altitude wetland (Bhusal, 2008; Yagi et al., 2010). The volume estimates help assess risks from climate change impacts on water availability (Thakuri et al., 2021a), and identifying areas of infilling informs lake sedimentation management strategies (Watson et al., 2019). Bathymetric data enables further limnological research on water quality, circulation and productivity (Bhusal, 2008).

The detailed bathymetric mapping provides critical high-resolution baseline data on the physical dimensions and submerged morphometry of the Panch-Pokhari. The quantification of parameters, like lake depth, volume, basin slope, and area provide integral information to improve hydrological and habitat modeling for conservation and management of this Ramsar designated wetland system (Kumar & Lamsal, 2016). The volume estimation fills an important data gap for water balance assessments, especially regarding water shortage risks during winter and drought periods anticipated under climate change. Mapping of sedimentation patterns allows identification of near-shore areas at higher risk of infilling to guide siltation management. The bathymetric data enables multi-disciplinary research on the limnology, water quality, biodiversity, and ecosystem functions of the lake complex. Thus, the modeling outputs significantly advance scientific understanding to support evidence-based planning for this ecologically vital lake system. The lake ecology faces threats from unsustainable tourism, pollution and habitat degradation (Raut et al., 2017; Bhusal, 2008; Watson, 2019). Managing visitor impacts and local communities' resource use is essential to safeguard the biodiversity and ecosystem services of this unique wetland ecosystem (Kumar & Lamsal, 2016).

Conclusions

This study generated new insights into the limnological characteristics and basin morphometry of the Panch-Pokhari through detailed bathymetric mapping and profiling. The analyses revealed the diverse morphology of the five lakes, with Lake 1 being the largest, deepest, and most voluminous. The quantification of physical parameters, like lake depth, and volume provides valuable data to improve hydrological and habitat modeling for conservation planning of wetland. The findings will help assess risks from climate change impacts on water availability as well as identify priority areas for siltation management. We suggest to expand the study of the lake complex and cover additional parameters, like water quality, underwater habitats, conduct seasonal/annual resurveys to quantify sedimentation rates, and morphometric changes over time and integrate bathymetric data with water quality, flow and watershed data to refine hydrological modeling.

Acknowledgements

This research was support by the NMA Research Grant (NMANMA-RP-2022-07).

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