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Bathymetric Survey and Sedimentation Assessment of Begnas and Rupa Lakes, Pokhara Valley

(Final Report)

Submitted By

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Abstract

Begnas Lake and Rupa Lake, two Ramsar-listed freshwater wetlands located within the Pokhara Valley of Nepal, play a vital role in sustaining aquatic biodiversity, supporting fisheries, irrigation, tourism, and providing ecosystem services to surrounding communities. However, increasing sediment influx from their watersheds, driven by watershed degradation, land-use change, road construction, and monsoon-induced erosion, has resulted in progressive loss of storage capacity and deterioration of lake morphology. To assess the current condition of these lakes and quantify ongoing sedimentation processes, a comprehensive bathymetric survey and sedimentation assessment were conducted during 2025/26.

The study employed a CHCNAV D390 RTK-integrated single-beam echo sounder combined with high-precision RTK-GNSS positioning to collect detailed bathymetric data. Depth measurements were processed using HydroSurvey 7.0+ and ArcGIS Pro to generate bathymetric maps, Digital Elevation Models (DEMs), contour maps, and lake morphometric parameters. Current bathymetric conditions were compared with historical survey datasets to evaluate temporal changes in lake morphology and estimate sedimentation rates.

The survey results indicate that Begnas Lake currently has a surface area of 305.6 ha, a maximum depth of 11.64 m, a mean depth of 7.49 m, and a storage volume of 22.74 million m^3. Comparison with previous surveys reveals significant long-term sediment accumulation, with an estimated cumulative volume loss of approximately 6.31 million m^3 since the early 1990s and a recent sedimentation rate of about 193,200 m^3/year. Rupa Lake presently covers 102.8 ha, with a maximum depth of 4.68 m, a mean depth of 2.86 m, and a storage volume of 2.91 million m^3. Relative to historical records, the lake has experienced a reduction of approximately 15.7% in surface area and an estimated sediment accumulation rate of 68,640 m^3/year, reflecting severe watershed-induced sedimentation.

The findings demonstrate that both lakes are undergoing continuous morphometric degradation and storage loss due to accelerated watershed erosion and sediment delivery. Rupa Lake is particularly vulnerable because of its shallow basin morphology and high watershed-to-lake area ratio. The study highlights the urgent need for integrated watershed management, including erosion control measures, slope stabilization, sediment retention structures, periodic bathymetric monitoring, and coordinated conservation interventions. The generated bathymetric database and sedimentation estimates provide an important scientific baseline for sustainable lake management, wetland conservation, and long-term monitoring of the Pokhara Lake Cluster.

Keywords: Bathymetric Survey, Sedimentation Assessment, Begnas Lake, Rupa Lake, Morphometric Analysis, Watershed Management, RTK-GNSS, Echo Sounder.

Acronyms and Abbreviations

Abbreviation / Acronym	Full Form
CHCNAV	CHC Navigation (instrument manufacturer)
DOFSC	Department of Forests and Soil Conservation
DHM	Department of Hydrology and Meteorology
DWG	Drawing (AutoCAD native file format)
DXF	Drawing Exchange Format
FAO	Food and Agriculture Organization of the United Nations
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GIS	Geographic Information System
Ha	Hectare
IDW	Inverse Distance Weighting
m	Metre
m^3	Cubic Metre
km	Kilometre
km^2	Square Kilometre
MSL	Mean Sea Level
NMEA	National Marine Electronics Association
RTK	Real-Time Kinematic
RTCIDP	Rupa Tal Conservation and Integrated Development Project
RUSLE	Revised Universal Soil Loss Equation
TIN	Triangular Irregular Network
UTM	Universal Transverse Mercator
USLE	Universal Soil Loss Equation
WGS84	World Geodetic System 1984

Table of Contents

List of Figures

List of Tables

Chapter 1. INTRODUCTION

1.1 Background

Wetlands and lakes across Nepal face serious and escalating threats from sedimentation, encroachment, pollution, and invasive species proliferation, all of which progressively undermine the sustainability of the aquatic and terrestrial ecosystems they support. The long-term viability of any wetland is fundamentally determined by the rate of sedimentation and the extent of encroachment driven by human activities or invasive vegetation. Left unmonitored and unmanaged, these pressures can irreversibly alter lake morphology, diminish water storage capacity, degrade ecological function, and ultimately threaten the livelihoods of communities that depend on these water bodies.

In the context of Nepal's mid-hill lakes, sedimentation represents the most pervasive and quantifiable threat. Steep surrounding terrain, intense monsoonal precipitation, deforestation, unregulated road construction, and expanding agricultural activity on vulnerable hillslopes collectively accelerate erosion and sediment delivery into lake basins. The consequences extend beyond simple volume loss — progressive infilling raises nutrient levels, promotes invasive weed proliferation, reduces biodiversity, and compromises the operational capacity of associated irrigation and water supply infrastructure.

Among Nepal's mid-hill wetlands, Begnas and Rupa Lakes of the Pokhara Valley are of particular significance and concern. Both lakes are listed under the Ramsar Convention as internationally important wetlands and form key components of the Lake Cluster of Pokhara Valley (LCPV). Despite their ecological, socioeconomic, and hydrological importance, both lakes are under mounting environmental pressure.

Begnas Lake, the second-largest lake in the Pokhara Valley, supports ecotourism, commercial fisheries, and the Begnas Irrigation Project — a critical agricultural water supply system established following the construction of a regulatory dam on the lake's western outlet in 1988. However, rapid land-use change on surrounding ridges and active sediment inputs from its primary feeder streams, the Syankhudi and Talbesi, have caused the progressive expansion of underwater sediment deltas at inlet zones, threatening the lake's deep-water storage capacity and accelerating eutrophication.

Rupa Lake, situated immediately east of Begnas and separated from it by the narrow Pachabhaiya ridge, is considerably more vulnerable owing to its shallow morphology and large watershed-to-lake area ratio of nearly 30:1. Historical records indicate that uncontrolled sedimentation and upstream land-use change between the 1970s and 2000s reduced the lake's surface area by approximately 30% and caused a measurable decline in maximum depth. This siltation, compounded by agricultural nutrient runoff, historically triggered invasive aquatic weed infestations covering up to 90% of the lake surface, pushing the ecosystem close to full terrestrialisation before community-led restoration efforts intervened. Despite these efforts, ongoing sediment influx from the Dhovan Khola and continued upstream watershed disturbance mean that the lake remains highly vulnerable. Both lakes therefore require regular, systematic scientific assessment to track ongoing morphological change, quantify sedimentation rates, and generate the reliable baseline data necessary for informed management and conservation decision-making.

Bathymetric surveying is the systematic measurement and mapping of underwater terrain depths and morphology which provides the most direct and reliable means of assessing lake volume, depth distribution, and morphological change over time. By comparing bathymetric surveys conducted at different points in time, it is possible to directly quantify volumetric loss attributable to sediment accumulation, identify zones of active deposition, and evaluate the pace of lake degradation. Key parameters derived from bathymetric surveys include surface area, maximum and mean depth, total water volume, depth-area and depth-volume relationships, and lakebed morphology — all of which are essential inputs for lake management, water resource planning, and conservation assessment.

Globally, bathymetric methods have evolved from rudimentary manual sounding techniques to sophisticated acoustic systems integrated with real-time satellite positioning. Modern surveys employ echo sounders coupled with DGPS or RTK-GNSS receivers, enabling continuous, high-density depth measurement with centimetre-level positional accuracy. The resulting datasets are processed within GIS environments to generate Digital Elevation Models (DEMs), contour maps, and morphometric analyses. For the present study, the CHCNAV D390 RTK Echo Sounder was employed, combining RTK-GNSS positioning with advanced acoustic profiling to ensure accurate and detailed mapping of the lakebed topography of both Begnas and Rupa Lakes.

A limited but progressively improving body of bathymetric data exists for Begnas and Rupa Lakes. The first systematic bathymetric survey of Begnas lake was conducted in 1992 and bathymentrc survey of Rupa Lake was conducted in 1994 Department of Forests and Soil Conservation (Then; Department of Soil Conservation and Watershed Management) using a microprocessor-controlled depth recorder of the type ROYAL RF-350A with high frequency of 200KHz. Subsequently, Rupa Tal Conservation Integrated Development Project re-surveyed Rupa Lake in 2017 using echo sounder instruments, providing updated morphometric information and enabling preliminary assessment of intervening volumetric change. In 2021, Thakuri et al. resurveyed Begnas Lake using an HDR 650 depth sounder, further refining depth and volume estimates.

These successive surveys collectively constitute the historical baseline against which the findings of the present study will be compared. By systematically contrasting current bathymetric measurements with datasets from 1992, 1994, 2017, and 2021, this study aims to produce robust, time-series estimates of sedimentation rates and morphological change for both lakes — directly informing the conservation and management priorities of the Department of Forests and Soil Conservation and contributing to the long-term monitoring framework for the Pokhara Lake Cluster.

1.2 Rationale of the Study

Begnas and Rupa Lakes are ecologically irreplaceable and socioeconomically vital components of the Pokhara Valley's wetland landscape. Both lakes directly sustain the livelihoods of tens of thousands of people — supplying water for downstream irrigation schemes, supporting commercial fisheries, and underpinning a growing ecotourism economy. Yet despite their significance, both lakes continue to experience progressive deterioration driven by accelerating sedimentation, watershed degradation, and insufficient upstream mitigation measures. As sediment gradually accumulates on the lakebed, usable water storage volume shrinks — meaning less water is available for irrigation during dry seasons, fish habitats are reduced, and the long-term viability of these ecosystems is increasingly compromised.

Understanding how much storage has already been lost, and at what rate loss is continuing, is only possible through systematic bathymetric surveying conducted at regular intervals and rigorously compared against historical measurements. The last comprehensive surveys of Begnas and Rupa Lakes were conducted in 2021 and 2015 respectively, leaving a significant and growing data gap at a time when both watersheds are experiencing intensifying land-use pressure. Without current and accurate depth and volume data, it is simply not possible to objectively assess the severity of ongoing degradation, identify where sediment is accumulating most actively, or make informed decisions about where and how to intervene.

The consequences of this data gap extend well beyond the lakes themselves. The Begnas Irrigation Project, which depends directly on the lake's regulated storage capacity, supplies water to extensive downstream agricultural land. As sedimentation reduces the effective storage volume of Begnas Lake, the reliability and seasonal availability of this irrigation supply is progressively undermined — with direct implications for food security and rural incomes in the surrounding communities. Similarly, Rupa Lake's shallow and silt-vulnerable basin means that continued unchecked sedimentation risks tipping the ecosystem toward irreversible degradation, threatening both the cooperative fisheries that local communities depend upon and the rich biodiversity the lake supports.

This situation is further compounded by gaps in institutional coordination. The management of Nepal's wetlands currently involves multiple agencies — including the Department of Forests and Soil Conservation, the Department of Hydrology and Meteorology, and local municipalities — without sufficiently clear divisions of responsibility or a shared, up-to-date scientific evidence base. This fragmentation hinders coordinated action on issues such as dredging, upstream watershed restoration, and shoreline protection. The authoritative bathymetric data generated by this study will provide a common, objective foundation upon which cross-institutional planning, targeted interventions, and evidence-based policy can be built.

The study is also directly aligned with Nepal's National Water Plan (2021), which prioritises the sustainable management of freshwater resources and the protection of critical water storage infrastructure across the country. At the international level, as components of the Ramsar-listed Pokhara Lake Cluster, Begnas and Rupa Lakes carry formal conservation obligations under the Ramsar Convention on Wetlands — obligations that require Nepal to maintain the ecological character of these sites through active monitoring and management. The findings of this study will directly support Nepal's fulfilment of these commitments, while also contributing to the Sustainable Development Goals: SDG 6 (Clean Water and Sanitation), by safeguarding freshwater storage and quality for dependent communities, and SDG 13 (Climate Action), by strengthening the evidence base for climate-resilient watershed management in a region highly exposed to intensifying monsoonal extremes.

By employing the CHCNAV D390 RTK Echo Sounder — integrating centimetre-level RTK-GNSS positioning with high-resolution acoustic depth profiling — this study will produce the most accurate and spatially detailed bathymetric dataset yet generated for both lakes. The results will provide clear, actionable information for lake managers, policymakers, and local communities, enabling better-informed decisions about dredging priorities, watershed restoration investments, and long-term strategies for preserving these irreplaceable freshwater ecosystems for future generations.

1.3 Objectives of the Study

General Objective:

To conduct a detailed bathymetric survey of Rupa Lake and Begnas Lake to determine their current depth, volume, and morphological characteristics for effective management and conservation.

Specific Objectives:

1. To measure and prepare bathymetric maps of Rupa and Begnas Lakes.
2. To analyze Lake Morphometric parameters, including surface area, depth profiles, and water storage capacity.
3. To compare the findings with available historical data to estimate sedimentation and morphological changes.

1.4 Scope of Work

This study encompasses a comprehensive bathymetric, morphometric, and sedimentation assessment of Begnas and Rupa Lakes, covering the following principal activities:

- **Literature and Data Review:** Review of existing literature, historical bathymetric surveys, topographic maps, and relevant spatial datasets to establish a comparative baseline for the assessment.
- **Survey Design and Field Data Collection:** Systematic survey grids and transect lines were designed to ensure complete and uniform lakebed coverage of both lakes. Field surveys were conducted using the CHCNAV D390 RTK-integrated echo sounder, recording water depth, geographic coordinates, and relevant environmental parameters with centimetre-level positional accuracy.
- **Data Processing and Quality Control:** Raw bathymetric data were processed and cleaned, quality control procedures applied, and missing or erroneous depth values corrected and interpolated to produce reliable, analysis-ready datasets. All processed data were exported in GIS-compatible formats to support advanced spatial and volumetric analysis.
- **Bathymetric Mapping and Morphometric Analysis:** Bathymetric contour maps, depth profiles. Key morphometric parameters — including surface area, maximum depth, mean depth, and total water storage volume — were calculated for both lakes.
- **Sedimentation and Change Assessment:** Current bathymetric findings were systematically compared with available historical survey data to quantify volumetric loss, estimate sedimentation rates, and characterise morphological changes over time. Findings were further correlated with watershed land-use changes to contextualise observed patterns of sediment accumulation.
- **Reporting and Dissemination:** Technical reports and GIS datasets, were prepared, and findings presented to relevant stakeholders to inform evidence-based lake management, watershed restoration, and conservation planning.

Chapter 2. STUDY AREA: Site Description and Environmental Context

2.1 Overview of Pokhara Lake Cluster

2.1.1 Ecological and Geographical Overview

Pokhara Valley, one of Nepal's foremost tourist destinations, is distinguished by its exceptional natural landscape encompassing wetlands, caves, forested hills, and the dramatic backdrop of the Annapurna Himalayan range, including peaks such as Machhapuchhre and Dhaulagiri. The Lake Cluster of Pokhara Valley (LCPV) comprises nine lakes — Phewa, Kamalpokhari, Gunde, Khaste, Neureni, Dipang, Maidi, Begnas, and Rupa — together with the Seti River system, spanning across Pokhara Metropolitan City, Annapurna Rural Municipality, and Rupa Rural Municipality. Distributed across an elevational range of 622 to 2,403 m asl, the lakes collectively cover approximately 262 km² of watershed area with around 9 km² of open water surface, each exhibiting distinct bathymetric profiles and sedimentation dynamics shaped by their respective watershed characteristics.

The valley lies within a high-rainfall climatic zone and is underlain by a complex hydrological system fed by key perennial sources, including Harpan Khola (Phewa), the Seti River (Kamalpokhari), Syangkhudi Khola (Begnas), and Dovan Khola (Rupa). These inflow systems serve as the primary conduits for sediment transport into the lake basins, with seasonal discharge variability — particularly during the monsoon — driving episodic sediment loading events that progressively alter lake morphometry and reduce storage capacity. The landscape morphology, characterised by alluvial plains and fans, ancient river terraces (locally known as *tars*), and steep hillslopes, further contributes to high erosion potential and sediment yield across tributary watersheds (Government of Nepal, 2015).

Rupa Lake (Rupa Tal) is a freshwater lake situated in the south-east of Pokhara Valley within Rupakot VDC, representing the third largest lake in the valley. Located at an altitude of approximately 600 m asl, the lake covers a surface area of about 1.35 km² with a mean water depth of 3 m and a recorded maximum depth of 6 m — shallow morphometric characteristics that render it particularly susceptible to sedimentation-induced depth reduction and accelerated eutrophication. The lake is elongated along a north–south axis and is fed by perennial streams draining a watershed of 2,663 hectares (26.63 km²), of which 52.54% is under forest cover, 41.55% under cultivation, 4% open water, 1.4% sand deposits, 0.28% scrubland, and 0.20% riverine water bodies. This land use composition — with over 40% cultivated area — is of direct relevance to sediment generation, as agricultural lands represent major sources of surface runoff and fine sediment influx to the lake. The primary inflow is from Talbesi Khola, while Dhovan Khola functions as a feeder stream with its outlet at Sistani Ghat. The lake lies within latitudes 28°08'N to 28°09'N and longitudes 84°06'E to 84°07'E.

The Malepatan Climatological Station at Pokhara serves as the nearest reference station for precipitation data pertaining to the Begnas–Rupa lake system. Climatic records indicate a humid subtropical regime, moderated by elevation, with summer temperatures averaging 25–33°C and winter temperatures ranging from approximately −2 to 15°C. The region receives high annual precipitation, predominantly concentrated during the monsoon season (July–September), with July recording the highest single-day rainfall of 265 mm in the Rupa Lake area. This intense monsoonal precipitation regime is the principal driver of watershed erosion, surface runoff, and sediment mobilisation into the lake system, making hydrological seasonality a critical factor in the interpretation of bathymetric survey data and sedimentation rate assessments.

2.1.2 Biodiversity, Socioeconomic Significance, and Environmental Services

The LCPV supports exceptionally rich biodiversity, attributable to its transitional position between the Palearctic and Oriental biogeographic realms. Recorded biodiversity encompasses 360 plant species, 140 bird species, 32 mammals, 27 fish, 24 reptiles, and 11 amphibians. Notably rare and threatened species present in the region include the critically endangered Baer's pochard, Indian vulture, clouded leopard, and Indian pangolin. The ecological integrity of this biodiversity is intrinsically linked to lake health: progressive sedimentation, by reducing water depth, degrading aquatic habitats, and elevating turbidity, poses a direct threat to native fish populations, waterbird foraging grounds, and macrophyte communities that underpin the food web structure of these wetland ecosystems.

The LCPV is home to over 378,000 people representing 101 ethnic groups and 67 languages, with socioeconomic indicators exceeding national averages, including a Human Development Index (HDI) of 0.576 and notably high female participation in economic activities. The wetlands of Begnas and Rupa, alongside Phewa, are central to local livelihoods through fisheries, agriculture, boating, and tourism. Economic valuations underscore the significance of these ecosystems: Phewa Lake alone generates over USD 279,000 annually in ecosystem services, while the Rupa Lake Restoration and Fishery Cooperative produces over USD 56,000 through sustainable fisheries management (Ramsar Sites Information Services, 2016). Sedimentation-driven loss of lake volume and productivity therefore carries direct socioeconomic consequences, threatening the fisheries yield, navigational depth, and aesthetic and recreational values upon which tourism and community livelihoods depend.

Community-led conservation mechanisms, including Payments for Ecosystem Services (PES) initiatives driven by local cooperatives and tourism stakeholders, play a critical role in sustaining conservation-based livelihoods across the valley. The findings of this bathymetric and sedimentation assessment are intended to directly support such management frameworks by providing quantitative evidence on current lake morphometry, sediment accumulation rates, and volumetric storage loss — information essential for prioritising dredging interventions, sediment trap placement, and watershed-level erosion control measures.

Water quality monitoring conducted during the study period provides supplementary context: sampling at Phewa Tal on 2082/02/20 recorded generally acceptable physicochemical conditions, though elevated pH (9.04), Chemical Oxygen Demand (29 mg/L), and turbidity (7 NTU) marginally exceeded guideline thresholds, indicative of low-level organic enrichment consistent with ongoing sediment and nutrient loading — conditions that reinforce the need for integrated bathymetric and water quality surveillance across the lake cluster.

2.2 Begnas Lake

2.2.1 Geographic Setting and Physical Characteristics

Begnas Lake is situated between 28°10′N–28°11′N latitude and 84°05′E–84°06′E longitude within Kaski District, Pokhara Metropolitan City, western Nepal, at an elevation of approximately 650 m asl. The second-largest lake in the Pokhara Valley, it forms part of the Pokhara Lake Cluster with a water volume of approximately 13.54 million m^3 (historical gross storage capacity up to 17.96 million m^3). Since 1988, water levels have been regulated by an earthen and concrete dam at the western outlet (Khudi Khola).

2.2.2 Climate and Hydrology

The Begnas watershed experiences a humid subtropical climate with four seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). Annual precipitation ranges from 3,800–4,000 mm, of which 80–85% falls during the monsoon, driving high seasonal discharge into the lake. Summer temperatures range from 25–32°C; winter temperatures from 10–15°C.

2.2.3 Ecosystem Services and Socioeconomic Importance

Begnas Lake is a Ramsar-designated wetland providing multiple ecosystem services, including agricultural irrigation via the Begnas Irrigation Project, commercial cage and capture fisheries, freshwater supply, and ecotourism (boating, scenic recreation, and wildlife observation). The lake also supports diverse aquatic fauna and provides habitat for resident and migratory bird species, contributing significantly to regional biodiversity.

2.2.4 Environmental Pressures and Conservation Concerns

The lake faces mounting pressures from land-use change, agricultural runoff, nutrient enrichment, invasive species, and sediment inputs from its primary feeder streams (Syankhudi and Talbesi). Progressive siltation has expanded underwater deltas at inlet zones, reducing deep-water storage capacity. Water quality sampling (2082/02/19 BS) recorded largely satisfactory conditions across most parameters — pH (8.22), turbidity (3.2 NTU), TDS, salinity, chloride, hardness, and total suspended solids — all within Nepal and

WHO guideline thresholds. However, Chemical Oxygen Demand was notably elevated at 45 mg/L, nearly double the WHO limit, indicating significant organic pollution. These pressures collectively underscore the need for regular bathymetric monitoring, integrated watershed management, and targeted conservation.

2.2.5 Lake Morphology and Area Changes

The morphological evolution of Begnas Lake has been strongly influenced by dam construction in 1988, which was built primarily for irrigation storage and fisheries development (Swar and Gurung, 1988). Prior to dam construction, the lake had a surface area of 2.4 km² and a maximum depth of 7.5 m (Ferro, 1978); afterwards, it expanded to approximately 3.03 km² with substantially greater storage capacity. Satellite-derived area estimates show overall stability since 1989, with apparent shrinkage in northern sections attributable to seasonal water-level fluctuation and remaining within mapping uncertainty (Table 1).

Table 1: Historical lake area of Begnas Lake derived from satellite imagery.

YEAR	LAKE AREA (KM²)
1976	2.10 ± 0.26
1989	2.96 ± 0.20
2009	2.83 ± 0.20
2023	3.00 ± 0.07

Bathymetric surveys conducted in 2019 recorded a maximum depth of 12.5 m, a mean depth of 6.6 m, and a volume of 13.54 million m³ (Thakuri et al., 2021a). Based on Google Earth, lake area was estimated at 3.0 ± 0.07 km² in 2023, and the watershed covers approximately 18.5 km².

2.2.6 Land Use and Land Cover Changes (2000–2020)

In 2020, the watershed was dominated by forest (50.5%), cropland (27.6%), water bodies (16.5%), wooded land (5.5%), and grassland (0.4%). Between 2000 and 2020, forest cover increased by 56%, while cropland, wooded land, and grassland declined by 34%, 37%, and 50%, respectively; built-up area remained negligible. Although forest recovery may reduce erosion and runoff, continued agricultural expansion has contributed to increased sediment delivery, nutrient loading, macrophyte proliferation, and progressive eutrophication (Lama, et al. 2018).

2.2.7 Soil Erosion and Sediment Dynamics

Estimated erosion rates in the Begnas watershed range from a mean of 48 t ha^{-1} yr^{-1} to a maximum of 259 t ha^{-1} yr^{-1} — (Lama, et al. 2018) lower than those recorded in the Phewa Lake watershed. Erosion hotspots are concentrated in the northern and eastern watershed, coinciding with cropland, settlements, and rural roads. Accelerated erosion contributes to lake sedimentation, shallowing, and eutrophication risk; agricultural practices remain the dominant driver of sediment production despite overall improvements in forest cover.

2.2.8 Water Quality

Water quality assessments ((Pant, et al. 2019)) indicate that Begnas Lake remains generally suitable for aquatic ecosystems, aquaculture, and irrigation, though several parameters signal increasing nutrient enrichment (Table 2). Dissolved oxygen (6.46 mg/L) is adequate for aquatic life, and BOD remains below permissible limits. However, pH (9.04) exceeds the WHO recommended range (6.5–8.5), likely reflecting carbonate weathering and elevated biological productivity. Elevated concentrations of phosphate (0.10 mg/L), nitrate (1.77 mg/L), ammonia (0.14 mg/L), and free CO_2 (13.32 mg/L) indicate increasing anthropogenic influence; phosphate enrichment in particular poses a significant eutrophication risk.

Table 2:Key water quality parameters for Begnas Lake (Pant et al., 2019).

Parameter	*Mean Value*	*Interpretation*
Temperature	26.73 °C	Warm subtropical lake
pH	9.04	Alkaline; above WHO guideline
EC	35.76 µS/cm	Low mineralization
TDS	25.42 mg/L	Very low dissolved solids
DO	6.46 mg/L	Adequate for aquatic life
BOD	26.28 mg/L	Moderate organic load
Nitrate	1.77 mg/L	Elevated; nutrient enrichment
Phosphate	0.10 mg/L	High eutrophication risk
Ammonia	0.14 mg/L	Elevated
Hardness	13.75 mg/L	Soft water
Free CO_2	13.32 mg/L	Above recommended level

2.2.9 Overall Assessment

Begnas Lake is a relatively small but ecologically significant Ramsar wetland whose hydrology and morphology have been substantially modified by dam construction since 1988. Watershed land-cover trends show net forest recovery, and erosion rates are lower than in the Phewa Lake watershed; however, agricultural activities continue to drive sediment and nutrient loading. Rising concentrations of nitrogen and phosphorus compounds indicate a gradual trajectory toward eutrophic conditions. Sustained watershed management — encompassing erosion control, nutrient reduction, and sustainable land-use practices — is critical for maintaining the long-term ecological integrity of the lake.

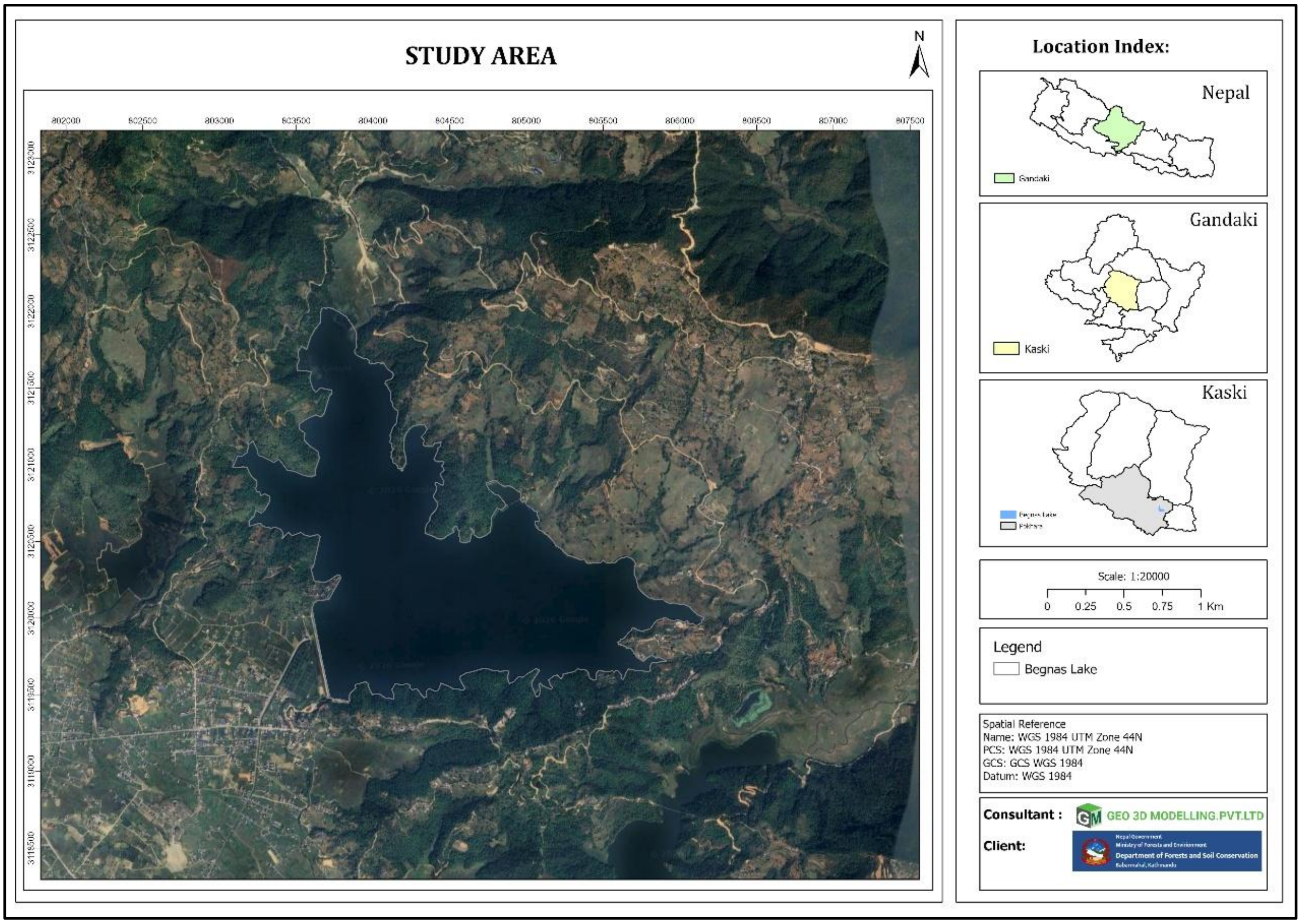

Figure 1: Google Earth Image of Begnas Lake and its watershed

2.3 Rupa Lake

2.3.1 Geographic Setting and Physical Characteristics

Rupa Lake is situated between 28°08′N–28°10′N latitude and 84°06′E–84°07′E longitude within Kaski District, western Nepal, immediately east of Begnas Lake and separated from it by the narrow Pachabhaiya ridge. The lake occupies an average elevation of approximately 600 m asl and extends in an elongated north-northeast to south-southwest orientation. The third-largest lake in the Pokhara Valley and a component of the Ramsar-listed Pokhara Lake Cluster, it has a surface area of approximately 1.0 ± 0.1 km², a maximum depth of 6.0 m, mean depth of 3.0 m, and a volume estimated between 2.55 and 3.25 million

m^3. Unlike neighbouring lakes, Rupa remains largely unregulated by major damming infrastructure; however, its surface area has historically contracted from approximately 135 ha to 1.00–1.11 sq km due to agricultural encroachment and progressive siltation. The lake is fed primarily by the Dobhan Khola and Taalbesi Khola from the eastern watershed and offers scenic views of the Annapurna and Manaslu ranges.

2.3.2 Climate and Hydrology

The Rupa watershed shares the humid subtropical climate of the broader Pokhara Valley, with four seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). Proximity to the Annapurna Himalayan range drives high annual precipitation of approximately 3,800 mm, the majority falling as intense monsoon rainfall between June and September. Summer temperatures range from 22–30°C; winter temperatures from 12–18°C.

2.3.3 Ecosystem Services and Socioeconomic Importance

Rupa Lake is an important ecological and socioeconomic resource for surrounding communities, supporting cooperative fisheries, agricultural irrigation, domestic water supply, groundwater recharge, and soil conservation. The lake provides critical habitat for over 150 species of resident and migratory wetland birds and holds significant religious and cultural value, with several temples and sacred sites along its shoreline. It is widely recognised as a model for community-led wetland governance through the Rupa Lake Restoration and Fisheries Cooperative, and supports community-based ecotourism centred on its biodiversity and mountain scenery.

2.3.4 Environmental Pressures and Conservation Concerns

Rupa Lake faces acute environmental vulnerability due to its exceptionally large watershed-to-lake area ratio of nearly 30:1. Massive sediment inputs from landslides and surface runoff via its principal feeder, the Dhovan Khola, combined with agricultural nutrient loading, have historically triggered severe invasive aquatic weed infestations and progressive wetland encroachment, placing the lake at risk of transitioning toward a terrestrial swamp. Additional pressures include eutrophication from nutrient enrichment and altered hydrological dynamics. These pressures highlight the need for regular bathymetric monitoring, active community mobilisation, and integrated watershed management.

2.3.5 Lake Area Dynamics (1976–2023)

Long-term observations from Google earth indicate that Rupa Lake has remained relatively stable in surface area over the past five decades (Table 3). Slight fluctuations are attributable to seasonal water-level variations, differences in image classification thresholds, and annual precipitation variability. A localised reduction was observed in the northeastern section of the lake. Unlike Begnas Lake, whose morphology was substantially altered by dam construction, Rupa Lake has maintained a largely natural hydrological regime controlled by seasonal watershed processes.

Table 3: Historical Lake area of Rupa Lake derived Google Earth.

YEAR	LAKE AREA (KM^2)
1976	0.91
2009	Slight decrease
2023	1.0 ± 0.1

2.3.6 Land Use and Land Cover Changes (2000–2020)

In 2020, the Rupa watershed was dominated by forest (75.9%), followed by cropland (14.7%), wooded land (5.3%), water bodies (4.1%), and grassland (0.2%). Between 2000 and 2020, forest cover increased by approximately 10%, while cropland declined by 29% and grassland and wooded land decreased by 38% and 20%, respectively; urban development remains sparse. The predominance of forest cover contributes to comparatively lower sediment production and better hydrological regulation than neighbouring watersheds. However, agricultural intensification in localised areas continues to be an important source of nutrient and sediment inputs to the lake (Thakuri, et al. 2021).

2.3.7 Soil Erosion and Sediment Dynamics

Estimated erosion rates in the Rupa watershed range from a mean of 39.6 t ha^{-1} yr^{-1} to a maximum of 259 t ha^{-1} yr^{-1} — lower than those recorded in both the Phewa and Begnas watersheds (LCDA 2024). Erosion hotspots are concentrated in the northern and eastern watershed, coinciding with cropland, rural settlements, and recently constructed road corridors. While high forest cover suppresses watershed-wide erosion, these localised disturbances generate significant sediment inputs that contribute to lake sedimentation, shallowing, nutrient transport, and seasonal eutrophication risk (LCDA 2024).

2.3.8 Anthropogenic Disturbances

Several emerging human pressures are increasing ecological stress on Rupa Lake. Recent earthen road development has elevated soil disturbance, surface erosion, and landslide susceptibility. Intensive cultivation in upper watershed areas contributes fertiliser runoff and organic matter loading. Construction of the Pachbhaiya Zoological Park in the northwestern watershed introduces additional risk of animal waste discharge and nutrient enrichment. Visible eutrophication has been reported in terminal portions of the lake, indicating progressive nutrient accumulation. If unmanaged, these pressures may accelerate ecological degradation and habitat loss.

2.3.9 Water Quality

Water quality assessments (Pant, et al. 2019) indicate that Rupa Lake remains generally suitable for aquatic ecosystems, irrigation, and livestock watering (Table 4). pH (7.87) falls within the WHO recommended range, dissolved oxygen (5.09 mg/L) is adequate for aquatic life, BOD remains below permissible limits, and nitrate and ammonia concentrations are within guideline values. Analysis of trace metals and additional parameters in 2022 confirmed compliance with Government of Nepal standards for livestock watering. However, phosphate concentrations (0.15 mg/L) substantially exceed the WHO guideline (0.02 mg/L), and free CO_2 (14.83 mg/L) is elevated above the recommended threshold of 10 mg/L, both indicating increasing anthropogenic nutrient influence and eutrophication risk.

Table 4: Key water quality parameters for Rupa Lake (Pant et al., 2019).

Parameter	*Mean Value*	*WHO Guideline*	*Interpretation*
Temperature	25.45 °C	—	Warm subtropical lake
pH	7.87	6.5–8.5	Within acceptable range
EC	52.33 µS/cm	—	Low mineralization
TDS	36.7 mg/L	—	Very low dissolved solids
DO	5.09 mg/L	≥5	Adequate for aquatic life
BOD	53.83 mg/L	<75	Within permissible level
Nitrate	2.46 mg/L	50	Acceptable
Phosphate	0.15 mg/L	0.02	Elevated; eutrophication risk
Ammonia	0.17 mg/L	1.5	Acceptable
Hardness	16.53 mg/L	<75	Soft water
Free CO_2	14.83 mg/L	<10	Elevated

2.3.10 Overall Assessment

Rupa Lake is a small but ecologically and socioeconomically significant freshwater lake within the Pokhara Valley. It has maintained a relatively stable surface area for over five decades, supported by a watershed in which forest covers approximately 76% of the area, yielding mean erosion rates lower than those of both the Phewa and Begnas watersheds. Nevertheless, expanding road networks, agricultural activities, and emerging infrastructure development are placing growing pressure on the lake ecosystem. Water quality remains generally acceptable, but elevated phosphate concentrations, high free CO_2, and visible eutrophication signal that nutrient enrichment is becoming a significant concern. Sustained watershed conservation, erosion control, and nutrient management will be essential to safeguard the long-term ecological health of Rupa Lake.

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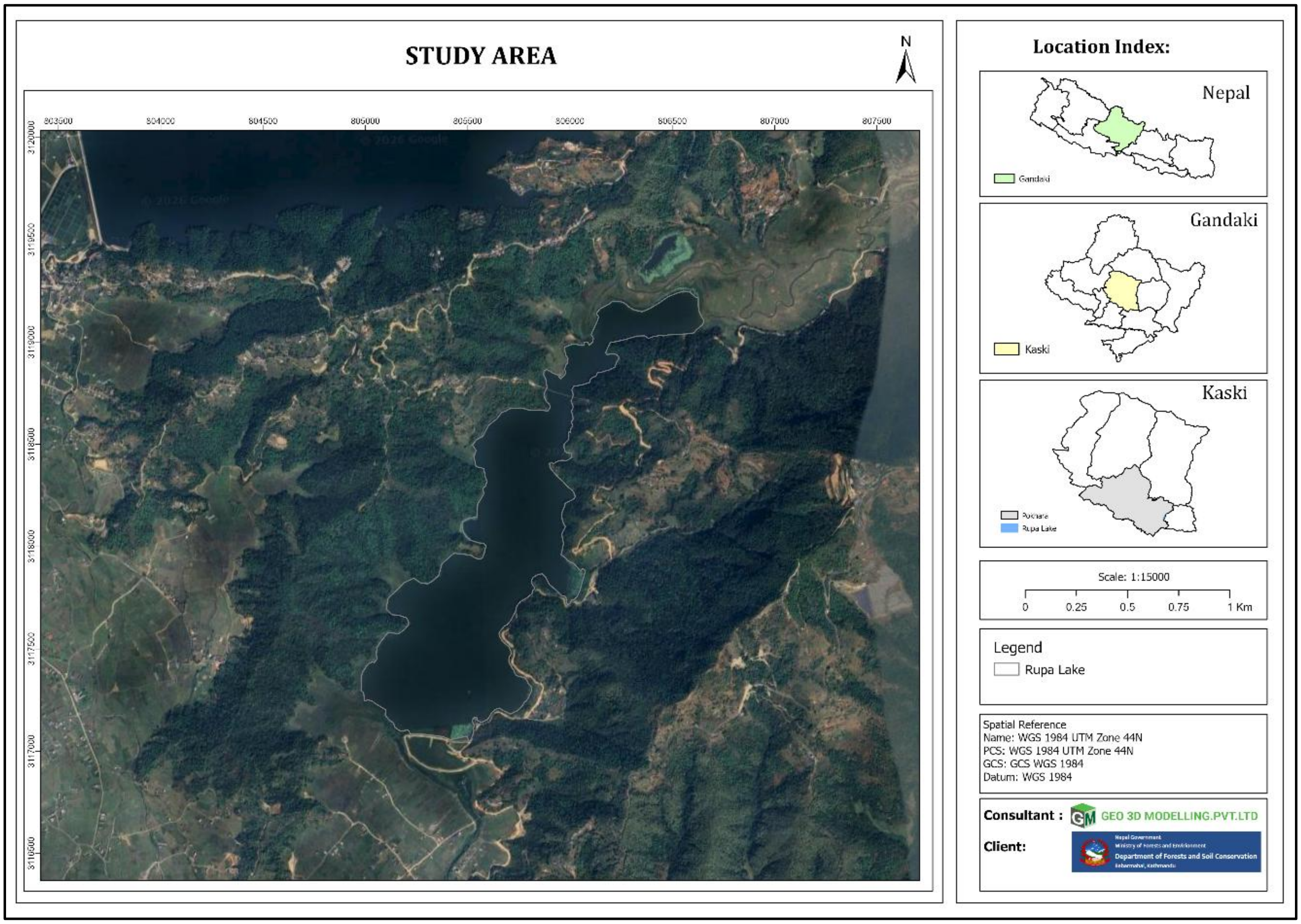


Figure 2: Google Earth Image of Rupa Lake and its watershed

Chapter 3. REVIEW OF LITERATURE

3.1 Bathymetric survey on Begnas Lake

The morphometric profile of Begnas Lake over the past five decades reveals a highly dynamic evolutionary trajectory dictated by an alternating cycle of artificial human engineering and subsequent watershed degradation. The baseline established by (Ferro and Swar 1978) described the water body with a surface area of 2.44 km^2, a maximum depth of 7.5 m and a mean depth of 4.5m . Following the construction of the western outlet regulatory dam on the Khudi Khola in 1988, the lake was transformed into a semi-regulated reservoir. This engineering intervention was captured by (Rai, et al. 1995), who documented a massive spatial expansion of the surface area to 3.28 km^2 and a structural volume increase to 17.96×10^6 m^3, alongside a maximum natural open-water depth of approximately 10.0 m and a mean depth of 6.6m . Our current survey results indicate that Begnas Lake now possesses a surface area of 3.056 km^2 , a maximum depth of 11.64 m, a mean depth of 7.49 m, and a total water volume of 22.74×10^6 m^3. Comparing our findings with the historical datasets highlights a clear trend of regulation-driven and seasonal water-level modification. This morphometric stabilization and apparent volumetric increase does not contradict the long-term sediment-driven contraction modeled by (Thakuri, et al. 2021), who reported a shrinking surface area of 2.98 km^2 and a reduced volume of 13.539×10^6 m^3 using 415 survey points. Instead, it demonstrates that the lake's total capacity is highly dependent on the operating threshold of the western outlet dam at the time of acoustic logging as well as the number of sample points taken for the survey. Surveying during high pool levels captures an inflated water column profile. However, the ongoing loss of physical deep-water storage capacity due to watershed degradation remains a critical factor. As identified by the Revised Universal Soil Loss Equation (RUSLE) modeling, intensive human land-use changes, specifically the proliferation of unengineered rural roads and terrace farming on steep, fragile slopes have accelerated soil erosion. This accelerated sediment load is transported primarily via the Syankhudi and Talbesi feeder streams, forming expanding underwater deltas at the lake inlets

3.2 Bathymetric survey on Rupa Lake

A review of available bathymetric and morphometric studies indicates that the physical characteristics of Rupa Lake have undergone notable temporal variations over the past four decades (Table 3). The earliest comprehensive bathymetric assessment conducted by (Ferro and Swar 1978) reported a lake surface area of 1.17 km^2, a water volume of 2.7×10^6 m^3, a maximum depth of 4.5 m, and an average depth of 2.3 m. Subsequently, (Rai, et al. 1995) documented an increase in both water volume (3.25×10^6 m^3) and maximum depth (6.0 m), while the lake surface area slightly decreased to 1.15 km^2. These findings suggest natural fluctuations in hydrological conditions and possible differences in survey methodologies and water levels during the measurement periods.

The bathymetric survey conducted under the (LIBIRD 2005) reported a further increase in surface area to 1.35 km² while maintaining a water volume of 3.25×10^6 m³. In contrast, later assessments indicated a declining trend in lake volume and depth.

More recent assessments by the (RTCIDP 2017) reported moderate improvements in morphometric parameters. The 2015 survey estimated the lake area at 1.11 km², water volume at 2.55×10^6 m³, and maximum depth at 4.0 m, whereas the 2017 study reported a surface area of 1.22 km² and a maximum depth of 6.0 m, with an average depth of 3.0 m. Overall, the reviewed studies reveal considerable variability in the morphometric characteristics of Rupa Lake over time. While part of this variability may be attributed to differences in survey techniques, reference water levels, and data processing approaches, the observed long-term decline in water storage capacity and depth in several studies highlights the ongoing influence of sedimentation and watershed-induced degradation processes. These findings underscore the importance of periodic bathymetric monitoring to assess lake evolution, quantify sediment accumulation, and support evidence-based lake and watershed management interventions.

According to (RTCIDP 2017), Rupa Lake contains approximately 1,343,828 m³ of sediment, representing roughly half the lake volume above the sandy substrate beneath the organic sediments, with an estimated solid mass of 2 million metric tons.

Before any decisions are made regarding the removal of lake sediments, it is essential to understand the rate at which sediments are accumulating due to watershed loading, as continued accumulation could eventually negate the effects of dredging. Sedimentation is a natural process in lakes, leading to the gradual buildup of material on the lake bottom over time. Lake sediment cores serve as valuable historical records of watershed conditions, providing information about vegetation types, geology, and changes in land use across different periods (RTCIDP 2017).

A study of historical sediment and nutrient accumulation rates in Rupa Lake indicates that surface sediments are relatively rich in organic matter. Furthermore, the mass sedimentation rate in Rupa Lake has risen progressively throughout the century, underscoring the growing pressure on the lake ecosystem (RTCIDP 2017).

Chapter 4. METHODOLOGY

4.1 Principles and Methods of Bathymetric Survey

4.1.1 Principles of Bathymetric Survey

Bathymetric surveying is founded on the physics of acoustic wave propagation in water, integrated with geospatial positioning systems to precisely measure and georeferenced underwater depths.

- Sound Wave Propagation and Depth Calculation: Echo sounders emit acoustic pulses that travel through the water column, reflect off the lakebed, and return to the transducer. Depth is calculated from the two-way travel time using:

$$Depth = (v \times t)/2$$

Where v is the speed of sound in water (approximately 1,480 m/s for freshwater) and t is the total travel time of the pulse. Since the speed of sound varies with water temperature, salinity, and pressure, appropriate corrections are applied to maintain depth accuracy.

- Acoustic Frequency: Survey frequency is selected based on water depth and required resolution. Higher frequencies yield finer resolution suited to shallow conditions, while lower frequencies penetrate greater depths with comparatively reduced precision.
- RTK-GNSS Positioning: Real-Time Kinematic (RTK) GNSS provides centimeter-level horizontal and vertical positioning by applying carrier-phase differential corrections from a fixed base station to a mobile rover on the survey vessel. This ensures each depth sounding is precisely geo-referenced.
- Lakebed Elevation Determination: The true elevation of the lakebed at each sounding point is derived by subtracting the measured acoustic depth from the RTK-derived transducer elevation, accounting for two key vertical offsets: the height from the GNSS antenna to the water surface (h_1), and the transducer draft — the distance from the water surface to the transducer face (h_2). This integration of acoustic depth measurement with RTK-GNSS positioning ensures centimeter-level accuracy in lakebed terrain mapping, which is essential for reliable volume estimation and sedimentation analysis.

4.1.2 Bathymetric Survey Methods

Several established methods exist for conducting bathymetric surveys, each suited to different survey scales, water depths, and accuracy requirements.

- Single-Beam Echo Sounding: A single transducer emits acoustic pulses vertically downward, recording one depth point per pulse. It is well suited to shallow lakes and small water bodies but requires closely spaced survey transects to achieve adequate spatial coverage. This method was employed in the present study using the CHCNAV D390 RTK-integrated echo sounder.
- Multi-Beam Echo Sounding**:** Multi-beam systems project a fan-shaped array of acoustic beams, simultaneously measuring depths across a wide swath in a single vessel pass. They produce high-resolution, full-coverage three-dimensional lakebed models and are most efficiently applied in large or deep water bodies.
- Airborne LiDAR Bathymetry: Laser pulses emitted from airborne platforms penetrate the water surface to map shallow and coastal environments. It is particularly effective in optically clear, shallow waters where acoustic methods may be less reliable.
- Side-Scan Sonar**:** Acoustic signals are emitted laterally from a towed transducer to generate high-detail imagery of the seafloor. Primarily used for detecting submerged objects and mapping substrate texture rather than precise depth measurement.

Of these methods, single-beam echo sounding integrated with RTK-GNSS positioning was selected for this study as the most appropriate approach for the shallow, enclosed freshwater environments of Begnas and Rupa Lakes, offering the required depth accuracy and spatial resolution within the practical constraints of the survey.

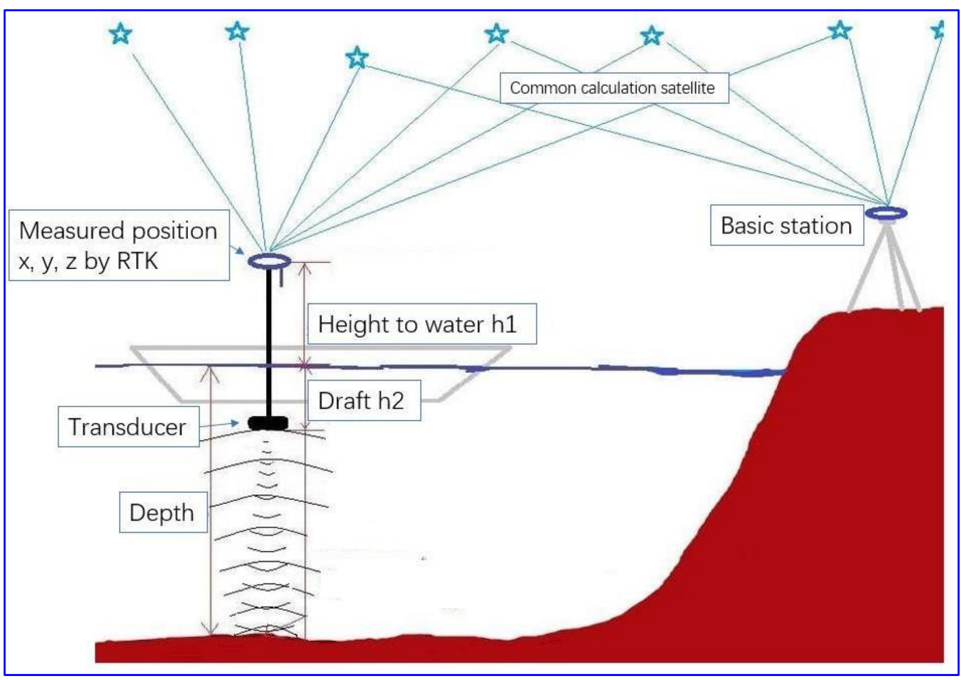


Figure 3: Working Principle of RTK ecosounder

4.2 Methodological Framework

Figure 4 presents the methodological framework adopted for the bathymetric survey and sedimentation assessment of Begnas and Rupa Lakes. The framework follows a systematic three-phase approach consisting of: (i) Pre-survey preparation, (ii) field survey and data collection, and (iii) data processing, analysis, reporting, and dissemination. This sequential methodology ensures the generation of reliable bathymetric data, accurate estimation of lake morphometry, and quantitative assessment of sediment deposition patterns.

4.2.1 Phase I: Pre-Survey Preparation

The first phase focused on establishing the technical, logistical, and institutional foundation for the study. The process commenced with an inception meeting involving relevant stakeholders and the Department of Forests and Soil Conservation (DoFSC) to define study objectives, methodologies, responsibilities, and expected outputs.

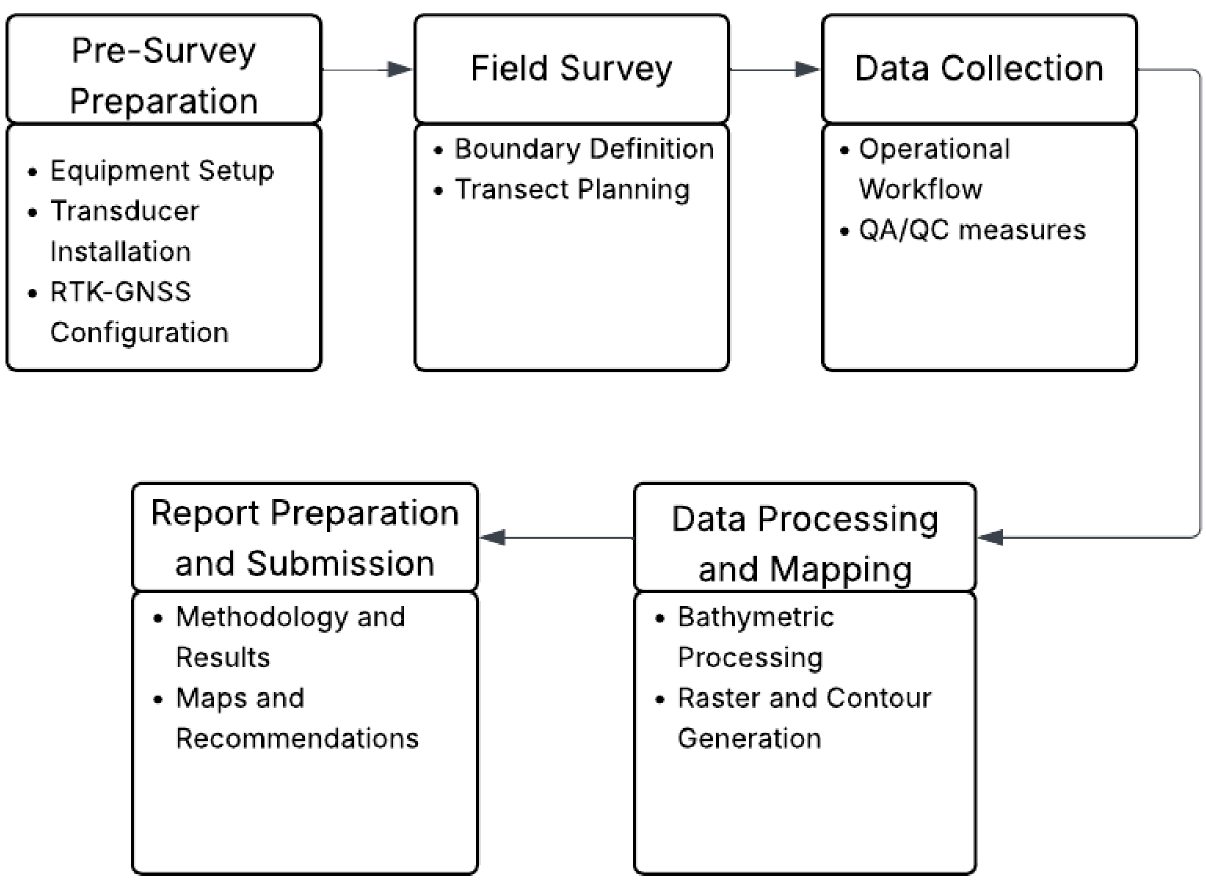


Figure 4: Methodological Framework for the study

A comprehensive review of previously published research, technical reports, academic studies, and project documents pertaining to Begnas and Rupa Lakes was undertaken. This included compilation and critical analysis of earlier bathymetric surveys, sedimentation assessments, limnological studies, watershed management reports, and any related investigations conducted in the Pokhara Valley. The reviewed literature served as a reference baseline for comparative analysis and for validating findings from the current assessment.

Based on the findings of the desk study, standardized data collection formats, field survey protocols, and quality assurance procedures were developed to ensure systematic and consistent data capture during field investigations. For area estimation, a map was prepared from the recent aerial RGB ortho image captured by Department of Mines and Geology (DMG) in 2024 was used for historical image data; Google earth was used.

4.2.1.1 Equipment Setup

All survey instruments were prepared, calibrated, and tested prior to field deployment to ensure operational accuracy and compatibility.

Transducer Installation

- The D390 echo sounder transducer was mounted vertically on the side of the survey boat using a transducer rod.
- It was submerged 30–40 cm below the water surface to ensure consistent and accurate depth measurements.
- The rod was securely fastened to avoid vibration or movement during the survey.

RTK-GNSS Configuration

- An RTK-enabled GNSS receiver (e.g., CHCI80) was connected to the D390 echo sounder via COM2/3/4 ports.
- NMEA settings were configured using HydroSurvey software with the following parameters:
    - Baud rate: 38400
    - Message output: GPGGA
    - Update rate: 1 Hz

HydroSurvey Software Setup

- A new project was created in HydroSurvey 7.0+, with the coordinate system set to WGS84 (UTM 44 projection).
- Key configuration parameters included:
    - Sound velocity: 1500 m/s (freshwater standard)

    - Waterline depth: Set based on transducer submersion (30 cm)

- Survey grid design:
    - Phewa Lake: 50 m × 50 m
    - Rupa Lake: 50 m × 50 m

4.2.1.2 Instruments Used

The following instruments and tools were used during the bathymetric survey:

- **CHCNAV D390 RTK-Echo Sounder** – for measuring water depth using single-beam sonar. (specs at annex).
- **Reach RS2 RTK-GNSS Receiver**– for acquiring precise spatial coordinates. (specs at annex).
- **HydroSurvey 7.0+ Software** – for data acquisition, real-time monitoring, and planning survey grids.
- **Controller with HydroSurvey and desktop with ArcGIS Pro (or related software) installed** – for data logging and post-processing.
- **Transducer Mounting Rod and Boat Setup** – for stable installation of echo sounder transducer.
- **Power Supply Units** – including external batteries and inverters to power all field equipment.

The major outputs of this phase included the inception report, a detailed work plan, survey design and transect layout, and the mobilization of personnel and equipment.

4.2.2 Phase II: Field Survey and Data Collection

4.2.2.1 Survey Design

Prior to commencing field measurements, preliminary depth information was obtained from a study conducted by the Department of Soil Conservation and Watershed Management in 1992-1994, supplemented by data from other available technical reports. This secondary data indicated that the range of lake depths which informed the planning and design of the field measurement programme.

4.2.2.2 Depth Measurement Approach

Prior to field deployment, all survey instruments were prepared, calibrated, and tested to ensure operational readiness. The CHCNAV D390 echo sounder transducer was mounted vertically on the survey boat using a transducer rod, submerged 30–40 cm below the water surface, and securely fastened to minimise vibration during data acquisition. An RTK-enabled GNSS receiver (Reach RS2) was connected to the echo sounder and configured via HydroSurvey software with a baud rate of 38,400, GPGGA message output, and a 1 Hz update rate. A new project was established in HydroSurvey 7.0+ using the WGS84 (UTM Zone 44) coordinate system, with sound velocity set to the freshwater standard of 1,500 m/s, (as per gudielines) a waterline depth of 30 cm corresponding to the transducer submersion depth, and a 50 m × 50 m survey grid applied to both lakes. In addition to the echo sounder and GNSS receiver, the survey employed a Reach RS2 RTK-GNSS receiver for precise spatial positioning. Transducer mounting rod for stable installation, and external batteries to power all field equipment throughout operation.

4.2.2.3 Operational Workflow

- The survey was conducted using Measure Mode in HydroSurvey.
- Data were recorded either at 1-meter spatial intervals or 1-second time intervals, depending on boat speed. In Begnas Lake, a paddle boat was used, maintaining an average speed of approximately **0.5–0.8 m/s**, while in Rupal, a rowing boat was used maintaing the speed of **0.5–0.8 m/s.**
- Real-time depth data and waterfall plots were continuously monitored to ensure data quality and coverage.

4.2.2.4 Boundary and Transect Planning

Lake boundaries were delineated using HydroSurvey's built-in drawing tools. Survey transects were planned with a 5–10% overlap between lines to ensure complete coverage, oriented along the longest axis of each lake.

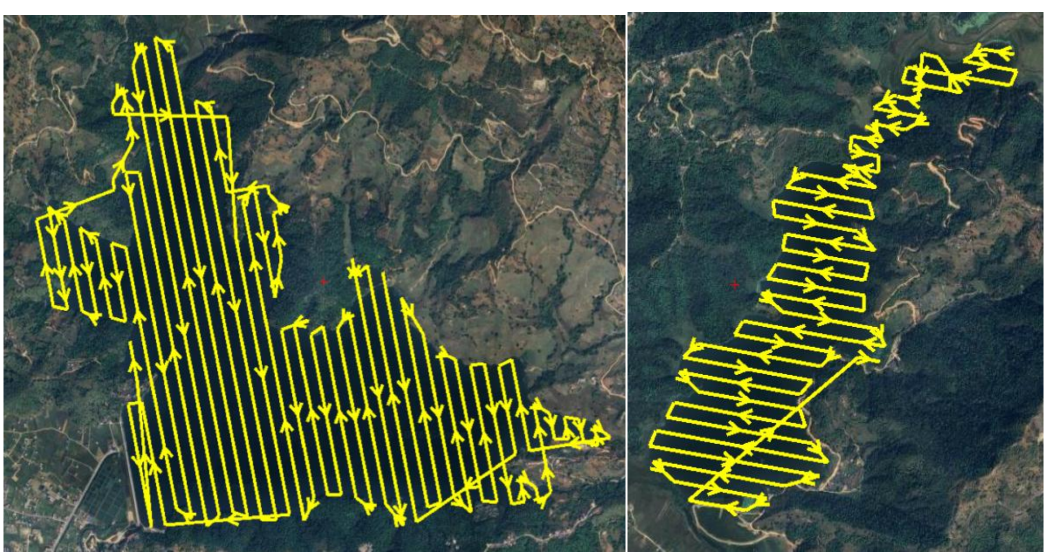


Figure 5: Transect design plan of Begans (Left) and Rupa (Right) Lake

Field operations were conducted from an inflated survey boat crewed by a boatman, two survey team member, and one field assistant. The survey team was responsible for confirming each measurement location, recording three-dimensional positional data comprising depth, latitude, and longitude.

Figure 6: Showing echo-sounder device being mounted on the paddle and rowing boat

Figure 7: Showing the actual line transects for Begnas (left)and Rupa (Right)Lake

4.2.2.5 Benchmark and Reference Datum Establishment

A geodetic benchmark traverse was established using a GNSS (DGPS) receiver by logging the data for more than 6 hours. Later, this data was processed using CSRS-PPP portal (https://webapp.csrs-scrs.nrcan-rncan.gc.ca/) for the precise coordinates. The coordinates of the Benchmark for Begnas Lake were 84^0 05' 33.69" E and 28^0 10' 00,03N and Reference Level of 682.6m and this point was established near the dam, while for Rupa Lake, a point near the Rupa fishery office was established with the coordinate of 84^0 06' 39.04" E and 28^0 08' 40.41"N and Reference Level of 633.28m.

4.2.2.6 Secondary Data Collection

Secondary spatial and hydrological data were systematically collected from relevant government organizations and technical institutions to supplement field observations and provide a baseline reference for the study. The following datasets were acquired:

- Topographic maps and aerial photographs at a scale of 1:50,000, obtained from the Topographical Survey Branch, Survey Department of Nepal.
- Previous technical reports on topographic and bathymetric surveys of the study lakes, including any historical depth, area, and volume data available from prior investigations.

These secondary data sources were reviewed, assessed for quality and relevance, and integrated into the study framework to guide field survey design, support data validation, and enable comparative analysis of changes in lake morphology and sedimentation over time.

4.2.3 Survey Limitations

Despite careful planning, the following limitations were encountered during the survey:

- Adverse weather, such as sudden rain and strong winds, affected data collection and boat stability in Begnas Lake.
- Wave disturbances introduced noise in sonar readings, particularly in Begnas's shallow zones, due to wind and other boat activities.
- GNSS signal loss occurred in areas surrounded by the trees at the edges in both the lakes.
- Underwater vegetation caused irregular sonar returns, making bottom detection difficult in parts of both lakes particularly in areas with presence of invasive species.
- Restricted shoreline access on the dam side of Begnas Lake and limited navigation in obstacle-prone zones in the Rupa Lake.

4.2.4 Quality Assurance and Quality Control (QA/ QC)

Quality Assurance and Quality Control (QA/QC) procedures were integral to all phases of the bathymetric investigation of Begnas and Rupa Lakes, conducted in the Pokhara Valley, Kaski District, Nepal. The study aimed to generate scientifically robust bathymetric maps, Digital Elevation Models (DEMs), morphometric parameters, and sedimentation assessments for both lakes; accordingly, rigorous QA/QC protocols were applied across all stages of the investigation, encompassing survey planning, field data collection, data processing, spatial analysis, and reporting. Particular emphasis was placed on minimizing positional errors, depth measurement uncertainties, interpolation artifacts, and inconsistencies attributable to variable lake conditions.

4.2.4.1 Instrument Calibration and Verification

Prior to field deployment, all hydrographic and positioning instruments were subjected to comprehensive calibration and operational testing to ensure measurement accuracy and system stability. The primary instruments employed in this survey included a single-beam echo sounder, a DGPS/RTK-GNSS receiver, water level measurement equipment, and integrated navigation and data logging software.

The echo sounder was calibrated in accordance with manufacturer specifications and the freshwater conditions characteristic of Begnas and Rupa Lakes. Sound velocity was set to approximately 1,500 m/s, consistent with freshwater temperature profiles recorded during the survey period, and transducer draft defined as the vertical distance between the water surface and the transducer head was precisely measured and incorporated into the system configuration.

Before the survey echo-sounder was calibrated using tape measure as shown in the figure below where wooden stick was dipped into the water and tape measure was used to measure the water depth and again echo-sounder was used at the same location to measure the depth, It was found the error with within plus minus 3 cm. Calibration checks were repeated periodically throughout the survey campaign, particularly following equipment transportation, battery replacement, or abrupt changes in environmental conditions.

Figure 8: Showing the Calibration of echo-sounder in the field

4.2.4.2 Survey Navigation

All survey transects were pre-designed and uploaded to the navigation software prior to field deployment to ensure systematic spatial coverage of both lakes. The survey vessel navigated along these predefined transect lines under continuous DGPS/RTK guidance to minimize deviation from planned survey paths.

4.2.4.3 DGPS/RTK Positional Precision Checks

Accurate positional data were considered fundamental to the reliable generation of bathymetric surfaces, contour maps, and sedimentation analyses for the two lakes. Stringent DGPS/RTK precision checks were therefore maintained throughout survey operations.

Before each survey session, satellite signal quality was verified, and the Positional Dilution of Precision (PDOP) was monitored to ensure acceptable positioning geometry. Correction signal status was recorded continuously, benchmark coordinates were validated at the start of each session, and repeat positioning checks were conducted at fixed onshore reference stations.

Particular attention was directed toward maintaining stable satellite connectivity in areas of Begnas and Rupa Lakes where signal reception was potentially compromised by surrounding topographic relief, steep valley walls, or riparian vegetation. Positional records failing to meet the established accuracy threshold were flagged during post-processing and excluded from the final dataset. Temporal synchronization between depth measurements and GNSS positional records was verified throughout to eliminate spatial mismatches between bathymetric soundings and their geographic coordinates.

4.2.4.4 Field-Level Data Quality Control

Daily QA/QC procedures were implemented during field operations to minimize data loss and enable early identification of errors. At the close of each survey day, raw data were backed up to redundant storage media, navigation tracks were reviewed for completeness and positional accuracy, depth profiles were inspected for anomalies, time synchronization between instrument streams was verified, and field metadata and observational notes were checked for consistency.

Field teams maintained standardized recording formats for all ancillary observations, including water level readings, meteorological conditions, instrument configuration settings, survey timing, and notable field observations. Photographic documentation was maintained throughout, covering field activities, shoreline morphology, benchmark locations, inlet zones, and visible sedimentation features at both Begnas and Rupa Lakes, in order to support post-survey data interpretation and reporting.

4.2.5 Phase III: Data Analysis and Interpretation

Following the completion of field surveys, all raw bathymetric datasets were subjected to systematic data cleaning and processing. This workflow encompassed the removal of duplicate records, noise filtering, elimination of outliers, correction of erroneous coordinates, water-level normalisation, and integration of data acquired across multiple survey sessions.

The cleaned point datasets were interpolated using established spatial interpolation algorithms, including Inverse Distance Weighting (IDW), Ordinary Kriging, and Triangulated Irregular Network (TIN) methods. The selection of the final interpolation method for each lake was guided by cross-validation performance metrics and the spatial distribution of survey points across the water body.

To evaluate the accuracy of the generated bathymetric Digital Elevation Models (DEMs) and contour maps, cross-validation analyses were performed by comparing interpolated surfaces against withheld survey points, repeat transect measurements, available historical depth profiles, and manually verified soundings. Statistical performance metrics, including Root Mean Square Error (RMSE), residual distributions, and interpolation consistency indices, were computed and reported to characterize the accuracy and reliability of the final bathymetric products.

4.2.5.1 DEM and TIN Preparation

Bathymetric contour data and topographic survey datasets were processed within an ArcGIS Pro environment to generate Triangulated Irregular Network (TIN) models of the study area. The TIN models were subsequently used as inputs for hydraulic geometry analysis and further spatial processing. Each TIN was converted into raster-based Digital Elevation Model (DEM) format to facilitate the preparation of slope maps, aspect maps, and a DEM-derived generalized geomorphic map of the lakebed and surrounding terrain.

4.2.5.2 Calculation of Lake Capacity

The shoreline was delineated through an integrated approach combining existing topographic map data, field verification surveys, and google earth. The delineated shoreline data were subsequently imported into a Geographic Information System (GIS) environment to precisely define the lake boundary polygon, which served as the foundational spatial layer for all subsequent bathymetric and volumetric analyses.

Lake storage capacity was determined from the bathymetric DEM and TIN surface models using three-dimensional volumetric analysis within the GIS environment. Storage volumes were computed at successive water surface elevation intervals to derive stage-storage and stage-area relationships for each lake. These relationships characterizes the hypsometric properties of Begnas and Rupa Lakes and provide the quantitative basis for assessing changes in lake capacity attributable to sedimentation over time. The resulting storage-elevation curves and capacity tables are presented in the relevant sections of this report.

4.2.5.3 Documentation and Metadata Management

Comprehensive metadata records were compiled for all survey datasets generated during this investigation. The metadata documentation encompasses the coordinate reference system adopted, full instrument specifications and calibration records, survey dates and session details, water level datums and reference benchmarks, data processing and quality control workflows, interpolation methods applied, and the results of accuracy and cross-validation assessments. This systematic documentation ensures the transparency, reproducibility, and long-term scientific utility of the Begnas and Rupa Lake bathymetric datasets for the Department of Forests and Soil Conservation (DoFSC), as well as for future researchers and practitioners engaged in watershed management and wetland monitoring in the Pokhara Valley region.

Field-collected bathymetric and topographic data were processed and analyzed using a combination of GIS software and Microsoft Excel. GIS tools were employed for spatial data management, surface interpolation, contour generation, DEM preparation, volumetric computation, and thematic map production. Microsoft Excel was used for tabular data organization, statistical calculations, and the derivation of storage-elevation relationships. All data processing steps were documented to ensure traceability and reproducibility of results.

4.2.5.4 Possible Errors and Degree of Uncertainty

Potential sources of error and uncertainty inherent in the survey methodology and data processing are acknowledged and assessed below.

Positional Error: GPS positional accuracy is subject to atmospheric signal delays, satellite geometry, and receiver precision. Positional errors in horizontal coordinates are estimated within the manufacturerspecified accuracy range of the instruments deployed, and their potential influence on the spatial referencing of depth soundings has been considered in the overall accuracy assessment.

Depth Measurement Error: Manual depth sounding using a weighted tape and thread is susceptible to errors arising from non-vertical deployment in the presence of wind-induced boat drift or water currents, tape elongation underload, and imprecise identification of the moment of bed contact. These factors may introduce minor random errors in individual depth readings, though their cumulative effect on interpolated surfaces is expected to be limited given the density of the measurement grid.

Interpolation Uncertainty: The accuracy of interpolated bathymetric surfaces is inherently dependent on the density and spatial distribution of survey points. In areas of complex lakebed morphology or limited sounding coverage, uncertainty of interpolation may be locally elevated. Cross-validation statistics reported in the DEM validation section quantify the overall magnitude of interpolation error for both lakes.

Water Level Fluctuation: Variations in lake water surface elevation between survey sessions, or between the time of sounding and the reference water level measurement, may introduce systematic depth offsets if not adequately corrected during data processing. Water-level normalization procedures applied during data cleaning are intended to minimize this source of error.

Overall Assessment: Notwithstanding the above limitations, the survey methods, grid density, and data processing procedures adopted in this investigation are considered appropriate for the purpose of lake bathymetry, storage capacity estimation, and sedimentation assessment at the scale and precision required by this study.

Chapter 5. Results

5.1 Sedimentation Surveys of Begnas Lake

5.1.1 Current Bathymetric Analysis of Begnas Lake

The present bathymetric survey of Begnas Lake employed a systematic depth-sounding approach. Raw survey data were converted into Triangular Irregular Networks (TIN) and subsequently resampled into a 5m × 5m raster grid using ArcGIS software. Morphometric parameters including contour lines, lake volume, and surface area were derived from the TIN using the Surface Contour and Surface Volume tools. The TIN method was selected over alternative interpolation techniques such as Kriging and Inverse Distance Weighting (IDW) owing to its superior reliability for bathymetric applications and wider adoption in literature.

The bathymetric contour map (Figure 9) reveals a highly irregular shoreline with several narrow inlets and embayment, indicative of complex basin geometry. Contour lines connect points of equal depth, enabling clear visualization of slope gradients and basin morphology. The deepest portion of the lake is located in the eastern section at coordinates 3,119,949.752 N and 805,566.379 E, where closely spaced contour lines indicate a steep underwater slope. The maximum recorded depth at this location is **11.64 m**.

The central and western regions of the lake exhibit wider contour spacing, reflecting gentler slopes and gradual depth transitions. The northern basin displays multiple localized depressions and irregular bathymetric features, while the southern region shows broader, smoother depth variations. Dense contour clustering near the eastern and northeastern margins corresponds to steep underwater terrain, whereas sparse spacing in the southwestern section reflects comparatively shallow and flat lake-bed conditions.

5.1.1.1 Elevation Distribution

The elevation map (Figure 10) uses a classified color gradient to represent spatial variation in underwater elevation. Low-elevation zones (deeper areas) are represented in red and orange, while higher-elevation zones (shallower areas) near the shoreline appear in yellow and green. The southeastern and central-eastern portions of the lake contain the lowest elevation zones, with the absolute deepest point situated in the southeastern basin. Elevation increases progressively toward the lake margins. The southeastern section presents a broad low-elevation region suggestive of a large deep-water storage area, while the northern arms exhibit narrower, more constricted elevation zones owing to the branching shoreline geometry.

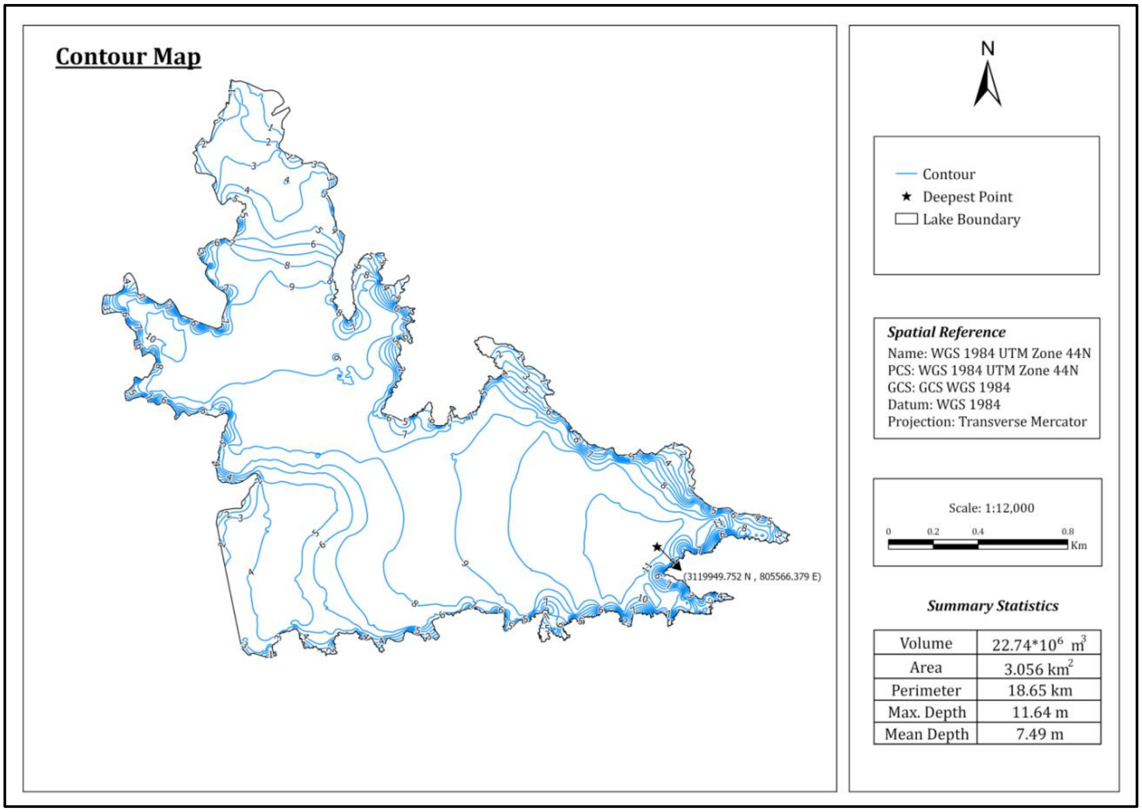


Figure 9: Contour Map of Begnas Lake

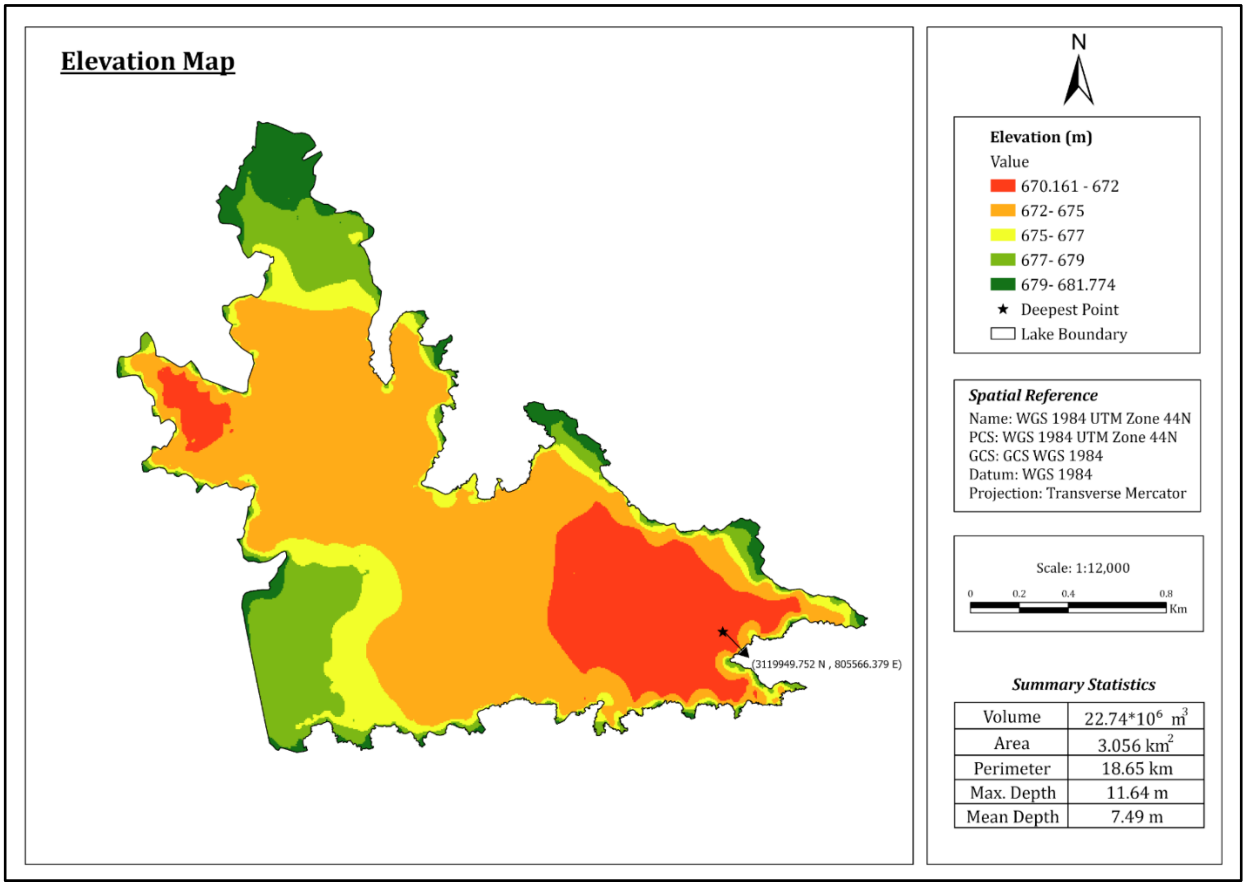
5.1.1.2 **Morphometric Summary**

The morphometric characteristics derived from the bathymetric analysis of Begnas Lake are summarized in Table 5.

Table 5: Morphometric Characteristics of Begnas Lake

PARAMETER	UNIT	VALUE
MAXIMUM DEPTH	m	11.64
MEAN DEPTH	m	7.49
PERIMETER	km	18.65
TOTAL LAKE AREA	sq km	3.05
TOTAL VOLUME	m^3	22.74×10^6

The lake spans a total area of 3.05 sq kma with a perimeter of 18.65 km, indicating a large and geometrically complex water body. The mean depth of 7.49 m relative to the maximum depth of 11.64 m suggests a moderately bowl-shaped basin. The estimated total storage volume of 22.74 × 10^6 m^3 provides a critical baseline for assessing future sedimentation-driven volume loss, particularly when compared against the volumetric decline documented in the literature review section.



Volume	22.74*10^6 m^3
Area	3.056 km^2
Perimeter	18.65 km
Max. Depth	11.64 m
Mean Depth	7.49 m

Figure 10: Bathymetric Map of Begnas Lake

5.2 Sedimentation Surveys of Rupa Lake

5.2.1 Current Bathymetric Analysis of Rupa Lake

The bathymetric contour map of Rupa Lake (Figure 11) employs a 1 m contour interval to depict depth variations across the basin. The deepest section of the lake is located near the central narrow portion at coordinates 3,118,390.656 N and 805,809.045 E, where closely spaced contour lines indicate a relatively steep underwater slope. The lake exhibits an elongated morphology with irregular boundaries. The southern basin displays broader and smoother contour patterns, reflecting a comparatively uniform bottom surface, while the central and northern sections show more irregular contour shapes associated with localized depth variations.

5.2.1.1 Elevation Distribution

The elevation map (Figure 11) similarly employs a classified color gradient. The central portion of the lake contains the lowest elevation zone, corresponding to its deepest area. Elevation increases progressively toward the lake margins. The southern section presents a broad low-elevation area suggestive of a larger deep-water storage zone, while the northern section displays narrower and more fragmented elevation zones owing to the constricted geometry of the lake at its northern end. Steeper gradients are observed in the central narrow section, and gentler slopes characterize the wider portions of the basin area

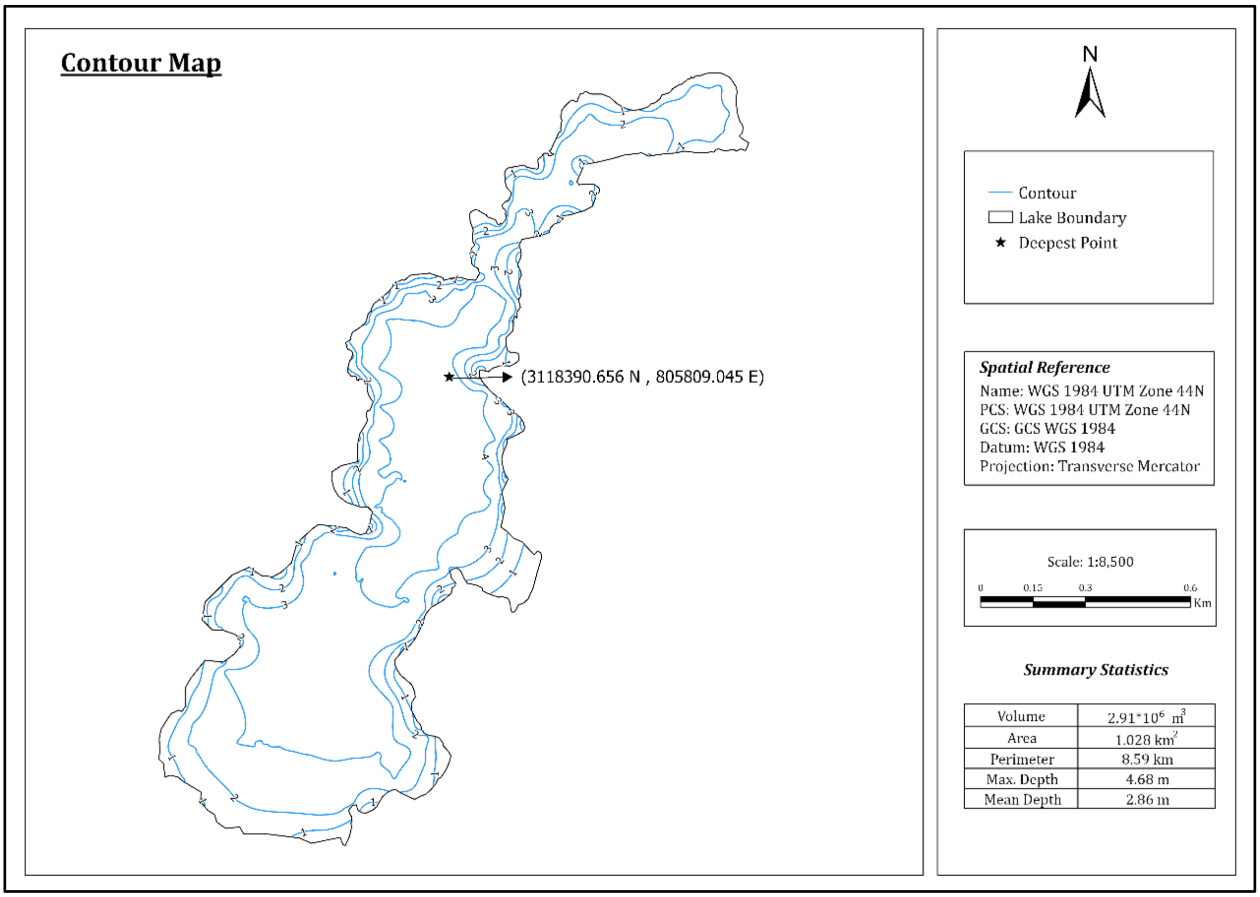


Figure 11: Contour Map of Rupa Lake

5.2.1.2 **Morphometric Summary**

The morphometric characteristics derived from the present bathymetric survey of Rupa Lake are presented in 6.

Table 6: Morphometric Characteristics of Rupa Lake

PARAMETER	UNIT	VALUE
MAXIMUM DEPTH	m	4.68
MEAN DEPTH	m	2.86
PERIMETER	km	8.59
TOTAL LAKE AREA	sq km	1.02
TOTAL VOLUME	m^3	2.91×10^6

The current total lake area of 1.02 sq km is notably lower than the 1.22 sq km recorded in the 2017 survey (RTCIDP 2017), indicating continued areal contraction of the lake. The total volume of 2.91×10^6 m^3 represents a marginal increase over the 2017 estimate of 2.26×10^6 m^3; however, this discrepancy is likely attributable to differences in survey methodology and datum references between the two studies rather than an actual increase in storage capacity. The maximum depth of 4.68 m and mean depth of 2.86 m confirm the shallow nature of Rupa Lake, making it highly vulnerable to continued sedimentation and eventual infilling.

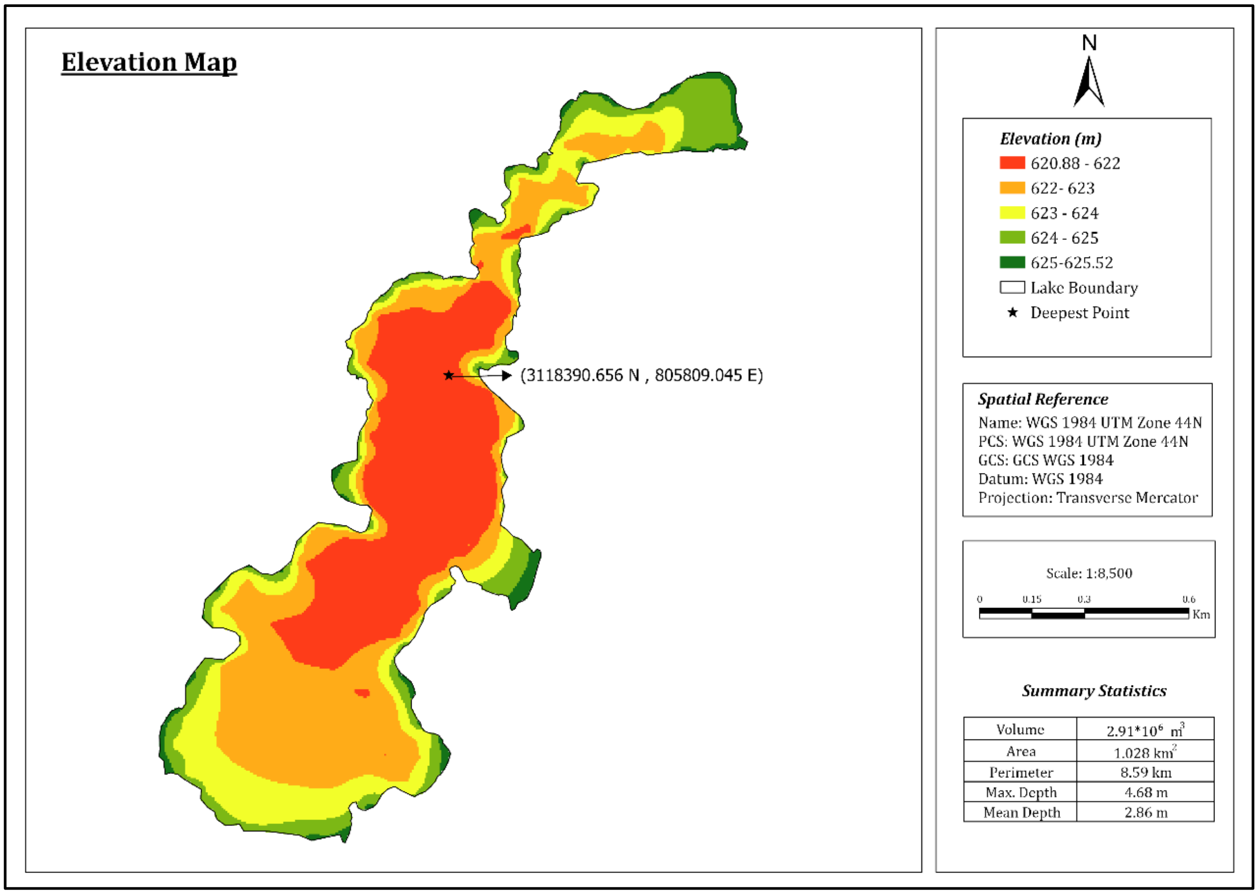


Figure 12: Bathymetric Map of Rupa Lake

5.2.2 Sedimentation, Morphometric Evolution, and watershed Degradation of Begnas Lake

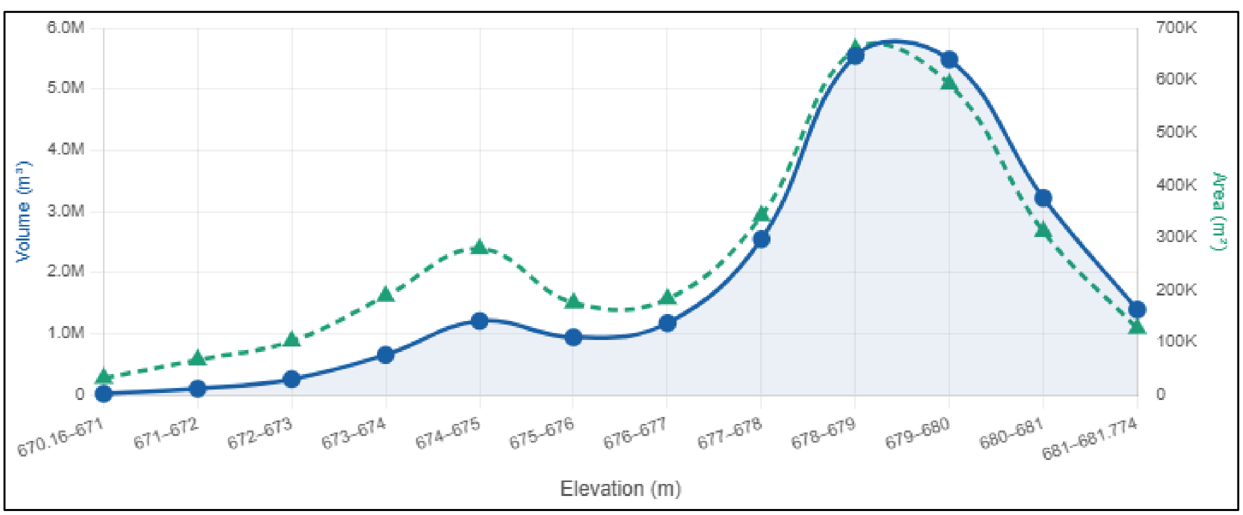


Figure 13: Elevation range versus Volume and Area curve of Begnas Lake

Figure 13 illustrates the distribution of water volume (m³) and surface area (m²) across elevation intervals ranging from 670.16 m to 681.774 m in Begnas Lake. The blue solid line represents volume, while the green dashed line represents surface area, both plotted against corresponding elevation bands on the x-axis.

Both parameters follow a broadly similar trend, remaining relatively low at lower elevations before rising markedly between the 677–678 m and 679–680 m intervals, where they reach their respective peaks. Volume peaks at approximately 5.7 million m³ and surface area at approximately 670,000 m² within the 679–680 m elevation band. Beyond this peak, both volume and surface area decline sharply toward the upper elevation limit of 681.774 m. A secondary, smaller peak is also observable around the 674–675 m interval, suggesting a minor bathymetric feature or shelf within the lake basin. Overall, the figure demonstrates that the bulk of the lake's storage capacity and surface extent is concentrated within the mid-to-upper elevation range, particularly between 678 m and 681 m.

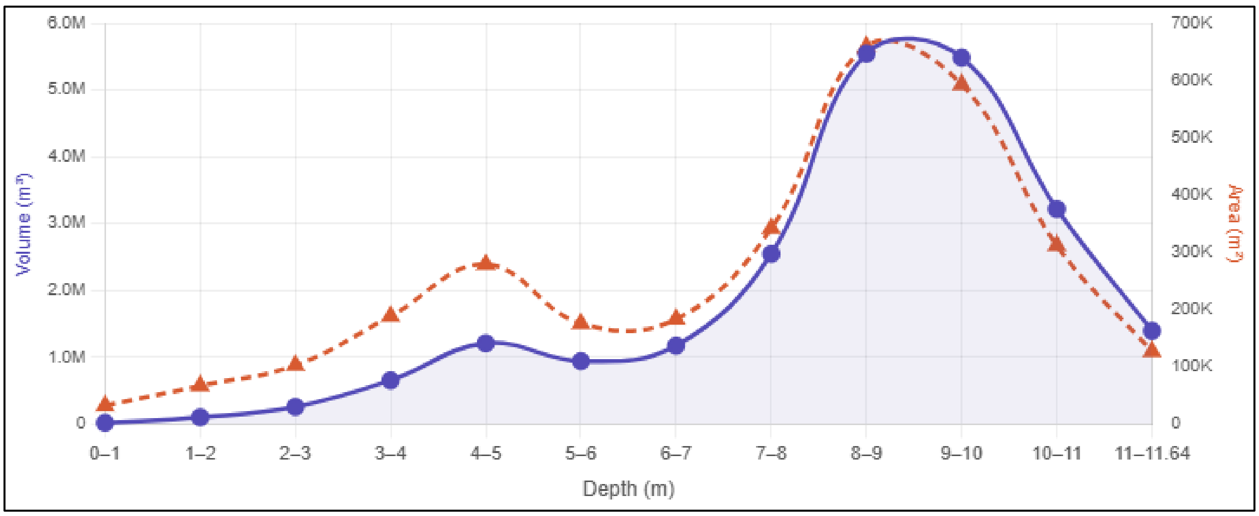


Figure 14: Depth range versus volume and area curve of Begnas Lake

Figure 14 presents the distribution of water volume (m³) and surface area (m²) across depth intervals ranging from 0 m to 11.64 m in Begnas Lake. The blue solid line represents volume, while the orange dashed line represents surface area, both plotted against corresponding depth bands on the x-axis.

Both parameters display a broadly comparable pattern across the depth profile. Values remain relatively low in the shallower zones between 0 m and 3 m, before rising moderately to a local peak at the 4–5 m depth interval, where volume reaches approximately 1.1 million m³ and surface area approximately 280,000 m². A slight decline follows between 5 m and 7 m, after which both volume and surface area increase sharply, reaching their maximum values within the 8–9 m depth interval, with volume peaking at approximately 5.7 million m³ and surface area at nearly 670,000 m². Beyond this point, both parameters decline steeply toward the maximum recorded depth of 11.64 m.

The presence of a secondary peak at 4–5 m suggests a distinct morphological feature within the lake basin, possibly indicative of a submerged terrace or transitional shelf. Overall, the figure demonstrates that the greatest storage volume and areal extent of Begnas Lake are concentrated within the deeper zones, particularly between 8 m and 10 m depth, reflecting the lake's bathymetric character.

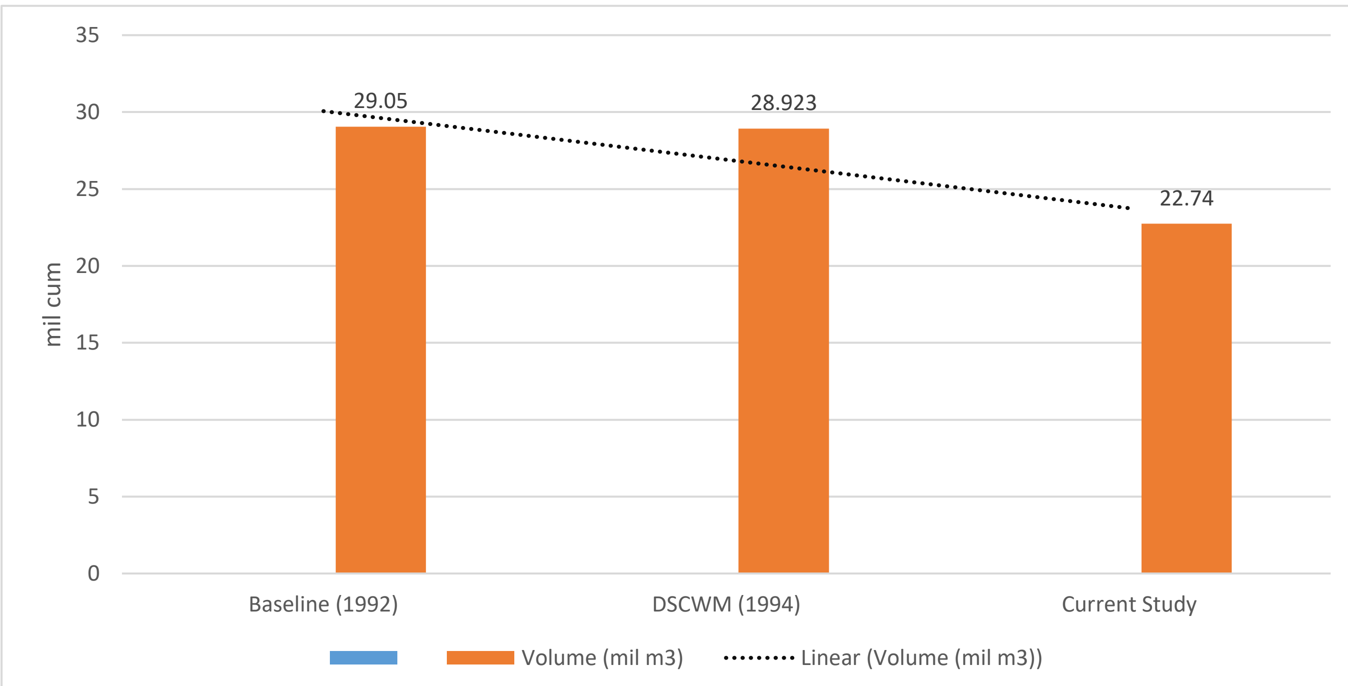


Figure 15: Trend of Volume change in Begnas Lake

The figure presents a bar chart illustrating the temporal change in total water volume (million m³) of Begnas Lake across three survey periods: the 1992 baseline, the DSCWM survey of 1994, and the current study.

The recorded volume declined progressively from 29.05 million m³ in 1992 to 28.923 million m³ in 1994, and further to 22.74 million m³ in the current survey, representing a cumulative volumetric loss of approximately 6.31 million m³ over the entire study period. Notably, the rate of volume loss between the 1992 baseline and the 1994 DSCWM survey was relatively modest at approximately 0.127 million m³, whereas the decline recorded between 1994 and the current study is substantially greater, suggesting an acceleration of sedimentation and storage capacity loss in more recent decades, likely driven by intensifying land-use pressures and watershed degradation within the watershed.

The fitted linear trend line reinforces this overall declining trajectory, with the negative slope of −3.155 indicating an average volumetric reduction of approximately 3.155 million m^3 per unit time interval across the survey periods. Collectively, the figure provides compelling visual and statistical evidence of the progressive physical degradation of Begnas Lake and underscores the urgency of implementing targeted sediment management and watershed conservation strategies to arrest further loss of storage capacity.

The analysis reveals a striking acceleration in the rate of sedimentation between the two study periods. Between 1992 and 1994, the annual volumetric loss was relatively modest at approximately 63,500 m^3/year, consistent with the earlier estimate reported by DSCWM (1994) of 62,951.5 m^3/year. However, between 1994 and 2026, the annual sedimentation rate increased nearly threefold to approximately 193,200 m^3/year, reflecting a significant intensification of watershed erosion processes over recent decades. This acceleration is consistent with documented land-use changes in the watershed, including the expansion of unengineered road networks and agricultural encroachment on steep slopes, both of which have substantially elevated sediment delivery to the lake. The overall long-term average sedimentation rate of approximately 185,600 m^3/year since the 1992 baseline underscores the severity and urgency of the sedimentation problem facing Begnas Lake and the critical need for integrated watershed and lake management interventions.

5.2.3 Sedimentation, Morphometric Evolution, and Watershed Degradation of Rupa Lake

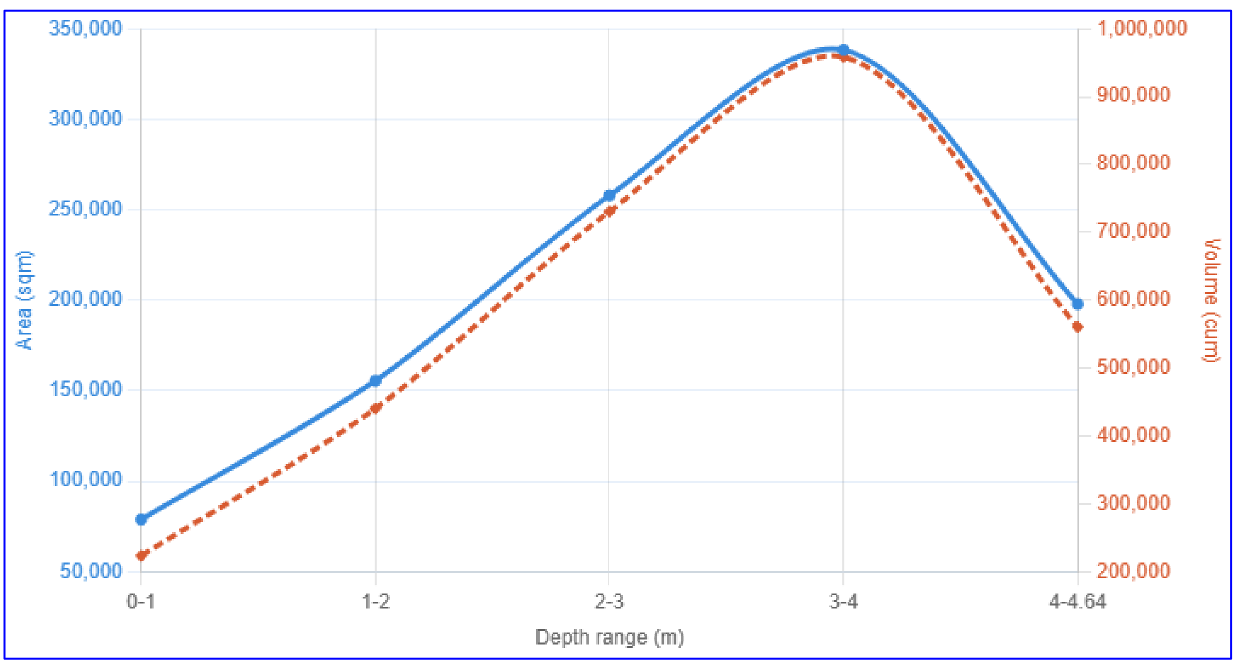


Figure 16: Depth range versus volume and area curve of Rupa Lake

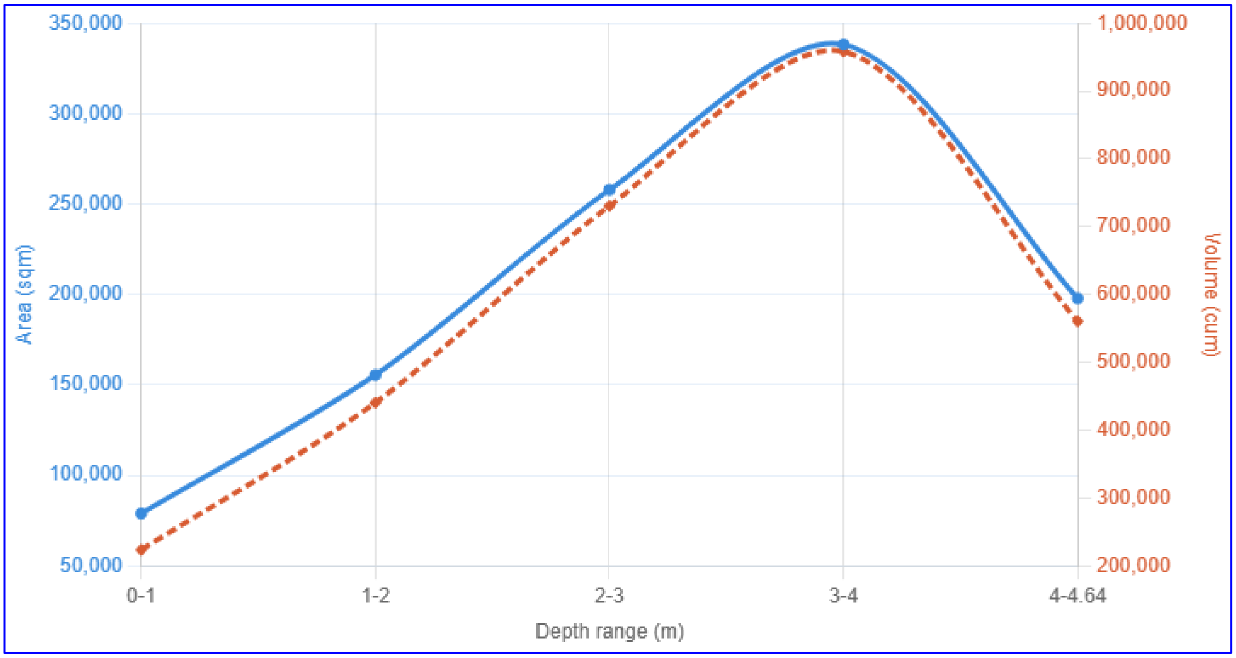


Figure 16 illustrates the distribution of surface area (m²) and water volume (m³) across depth intervals ranging from 0 m to 4.64 m in Rupa Lake. The blue solid line represents surface area plotted against the left y-axis, while the orange dashed line represents volume plotted against the right y-axis, with both parameters displayed across corresponding depth bands on the x-axis.

Both parameters follow a closely parallel and broadly unimodal trend throughout the depth profile. Starting from relatively modest values at the shallowest interval of 0–1 m, where surface area measures approximately 80,000 m² and volume approximately 220,000 m³, both parameters increase steadily and consistently through successive depth intervals. They reach their respective maximum values within the 3–4 m depth band, where surface area peaks at approximately 335,000 m² and volume at approximately 960,000 m³. Beyond this point, both parameters decline sharply toward the maximum recorded depth of 4.64 m, with surface area falling to approximately 195,000 m² and volume to approximately 550,000 m³.

The close correspondence between the area and volume curves across all depth intervals reflects a relatively uniform and bowl-shaped basin morphology, with no pronounced secondary peaks or bathymetric irregularities, unlike the more complex profile observed in Begnas Lake. The concentration of maximum storage capacity and areal extent within the 3–4 m depth zone, combined with the shallow overall depth range of just 4.64 m, underscores the comparatively limited bathymetric depth and storage capacity of Rupa Lake, indicating its heightened vulnerability to sedimentation and eutrophication processes.

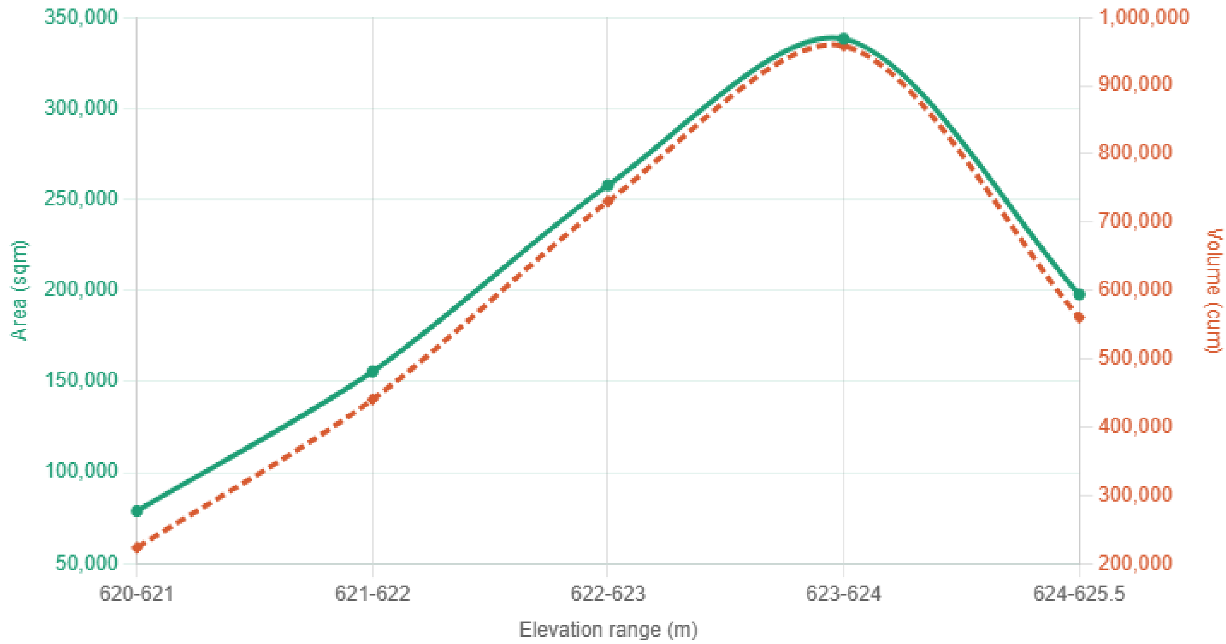


Figure 17: Elevation range versus volume and area curve of Rupa Lake

The figure presents the distribution of surface area (m^2) and water volume (m^3) across elevation intervals ranging from 620 m to 625.5 m in Rupa Lake. The green solid line represents surface area plotted against the left y-axis, while the orange dashed line represents volume plotted against the right y-axis, with both parameters displayed across corresponding elevation bands on the x-axis.

Both parameters exhibit a closely parallel and consistently unimodal trend across the elevation profile. At the lowest elevation interval of 620–621 m, surface area begins at approximately 80,000 m^2 and volume at approximately 220,000 m^3, after which both increase steadily through successive elevation bands. Maximum values are attained within the 623–624 m elevation interval, where surface area reaches approximately 335,000 m^2 and volume approximately 960,000 m^3. Beyond this peak, both parameters decline sharply toward the uppermost recorded elevation of 625.5 m, with surface area reducing to approximately 195,000 m^2 and volume to approximately 550,000 m^3.

The near-identical trajectories of the area and volume curves across all elevation bands are indicative of a morphologically uniform and relatively simple basin geometry, with no discernible secondary peaks or structural irregularities. The concentration of maximum areal extent and storage capacity within the narrow 623–624 m elevation band, combined with an overall elevation range of only 5.5 m, further reinforces the characteristically shallow and bathymetrically constrained nature of Rupa Lake. This limited vertical relief renders the lake particularly susceptible to the adverse effects of progressive sedimentation and nutrient enrichment.

Chapter 6. Discussion

6.1.1 Past Sedimentation Surveys of Begnas Lake

Three bathymetric surveys have been conducted by Department of Soil Conservation and Watershed Management on Begnas Lake to monitor volumetric changes due to sedimentation. The first survey, carried out in December 1992, recorded a total lake volume of 29.049 million m^3. A subsequent survey in January 1994 measured the volume at 28.986 million m^3, and a third survey in December 1994 recorded 28.923 million m^3. These successive measurements indicated a consistent decline in lake volume, yielding an average annual volumetric loss of approximately 62,951.5 m^3.

Given that the watershed area of Begnas Lake extends over 1,821 hectares, and assuming spatially uniform soil loss across the watershed, the estimated annual erosion rate equates to approximately 34.56 m^3/ha, corresponding to a mean annual soil layer loss of 3.45 mm. This rate reflects the ongoing sediment influx from the watershed and highlights the progressive infilling of the lake basin over time.

6.1.2 Past Sedimentation Surveys of Rupa Lake

The Rupa Lake watershed encompasses a total area of 2,663 hectares (26.63 km^2), characterised by a diverse mosaic of land use types, with forest cover constituting the dominant category at 52.54%, and followed by cultivated land (41.55%), the Lake Surface (4%), sandy deposits (1.4%), shrubland (0.28%), and open river water bodies (0.20%). According to the Rupa Tal Integrated Development Project (2017), the lake has been subjected to escalating sedimentation pressures over recent decades, driven primarily by the Talbesi Khola, which transports considerable volumes of sediment during the monsoon season, causing the riverbed at the lake inlet to rise by as much as 3 metres. The hillside access road situated above the lake further compounds these inputs as a secondary source of anthropogenic sediment contribution. As a consequence of these cumulative pressures, the effective surface area of the lake has contracted substantially, with only approximately 1.35 sq km of the total mapped area of 1.63 sq km remaining inundated. Should current rates of sedimentation and lake shrinkage persist without adequate intervention, the lake is projected to face severe ecological and hydrological degradation within the coming decade, underscoring the urgent need for targeted watershed management and sediment control measures. Key baseline metrics from the 2017 survey are as in Table 7 follows:

Table 7: Key baseline metrics of Rupa Lake

PARAMETER	VALUE
LAKE AREA	1.22 sq km
LAKE VOLUME	2.26×10^6 m³
MAXIMUM LENGTH	2,050 m
MAXIMUM WIDTH	854 m
MEAN WIDTH	420 m
MAXIMUM DEPTH	6 m
MEAN DEPTH	3 m

These figures provide the reference point against which the results of the present survey are compared.

6.2 Comparative Assessment and Implications

The bathymetric surveys of Begnas and Rupa Lakes collectively highlight contrasting morphometric profiles and sedimentation trajectories. Begnas Lake, with a substantially larger area (305.6 ha) and volume (22.74×10^6 m³) and a deeper basin (maximum depth 11.64 m), currently retains greater hydrological resilience relative to Rupa Lake. Nevertheless, the historical sedimentation data for Begnas (averaging 62,951.5 m³/yr of volume loss) underscores that it too faces progressive infilling over the long term if watershed erosion is not mitigated.

Table 8: Morphometric characteristics of Begnas Lake as recorded in 1992, 1994 and the current bathymetric study

MORPHOMETRIC PARAMETER	UNIT	BASELINE (1992)	DSCWM (1994)	CURRENT STUDIES
WATER LEVEL	m	655.7	655.7	680.5
MAXIMUM DEPTH	m	13.8	13.28	11.64

MEAN DEPTH	m	9.4	11.62	7.49
TOTAL LAKE AREA	sq km	3.10	3.10	3.05
VOLUME (MIL M3)	mil m^3	29.05	28.923	22.74

Table 8 presents a comparative overview of key morphometric parameters of Begnas Lake across three temporal datasets: the 1992 baseline survey, the Department of Soil Conservation and Watershed Management survey of 1994 (DSCWM, 1994), and the current study. The parameters examined include water level, maximum depth, mean depth, total lake area, and total water volume.

The water level remained constant at 655.7 m between the 1992 baseline and the 1994 survey but rose markedly to 680.5 m in the current study, reflecting the influence of dam regulation and differing survey conditions on the recorded pool elevation. Maximum depth declined progressively across the three periods, from 13.8 m in 1992 to 13.28 m in 1994, and further to 11.64 m in the current survey, representing a cumulative reduction of 2.16 m over the study period. This consistent decrease is indicative of ongoing sediment deposition on the lakebed. Mean depth, however, exhibits a less uniform trend: it increased from 9.4 m in 1992 to 11.62 m in 1994 before declining substantially to 7.49 m in the current survey. This fluctuation likely reflects methodological differences in bathymetric survey techniques, spatial coverage, and the number of sampling points employed across different studies, in addition to the influence of varying water levels at the time of survey.

Total lake area remained relatively stable between the 1992 and 1994 surveys at 3.10 sq km, with a marginal reduction to 3.05 sq km recorded in the current study, suggesting limited lateral contraction of the lake extent over time. The most pronounced and ecologically significant change is observed in total water volume, which decreased from 29.05 million m^3 in 1992 to 28.923 million m^3 in 1994, and declined substantially further to 22.74 million m^3 in the current survey. This cumulative volumetric loss of approximately 6.31 million m^3 since the 1992 baseline underscores the severity of long-term storage capacity reduction driven by progressive sedimentation and watershed degradation. Collectively, these data highlight a clear trajectory of physical deterioration in Begnas Lake and reinforce the need for urgent and sustained management interventions at both the lake and watershed scale.

Rupa Lake, by contrast, presents a more urgent concern. Its shallow basin (maximum depth 4.68 m, mean depth 2.86 m), contracted areal extent (1.02 sq km versus a historical 1.22–1.35 sq km), and the documented 3 m rise in the Talbesi Khola river bed collectively indicate advanced sedimentation stress. The lake's continued shrinkage poses significant risks to water storage, biodiversity, and the communities dependent on the lake ecosystem.

These findings underscore the need for integrated watershed management interventions — including sediment trapping structures, riparian revegetation, and road drainage improvements — to reduce sediment loads entering both lakes. Periodic bathymetric monitoring is equally essential to track volumetric changes over time and to inform evidence-based conservation policy.

Siltation surveys conducted on Begnas Lake over a period of two years recorded a progressive decline in the lake's total volume. The December 1992 survey established a baseline volume of 29.049 million m^3, which decreased to 28.986 million m^3 by January 1994, and further to 28.923 million m^3 by December 1994 (DSCWM, 1994). Based on these measurements, the average annual reduction in lake volume was calculated at approximately 62,951.5 m^3, reflecting a consistent and ongoing trend of sedimentation. The watershed area draining into Begnas Lake spans 1,821 hectares, and assuming soil loss is distributed uniformly across the entire watershed, the estimated annual erosion rate amounts to approximately 34.56 m^3 per hectare, equivalent to a loss of roughly 3.45 millimeters of topsoil annually (DSCWM, 1994). These figures highlight the considerable scale of sediment influx into the lake and underscore the pressing need for watershed-level conservation and erosion management interventions.

The morphometric profile of Begnas Lake over the past five decades reveals a highly dynamic evolutionary trajectory dictated by an alternating cycle of artificial human engineering and subsequent watershed degradation. The baseline established by Ferro and Swar (1978) described the water body with a surface area of 2.44 km^2, a maximum depth of 7.5 m, and a mean depth of 4.5 m. Following the construction of the western outlet regulatory dam on the Khudi Khola in 1988, the lake was transformed into a semi-regulated reservoir. This engineering intervention was captured by Rai et al. (1995), who documented a substantial spatial expansion of the surface area to 3.28 km^2 and a structural volume increase to 17.96×10^6 m^3, alongside a maximum open-water depth of approximately 10.0 m and a mean depth of 6.6 m. Current survey results indicate that Begnas Lake now possesses a surface area of 3.056 km^2, a maximum depth of 11.64 m, a mean depth of 7.49 m, and a total water volume of 22.74×10^6 m^3. The current data indicates a seasonal or regulatory gain of 1.24×10^6 m^3 in storage capacity, reflecting the strong influence of dam operations on observed water levels at the time of survey.

This apparent volumetric increase does not contradict the long-term sediment-driven contraction modeled by Thakuri et al. (2021), who reported a shrinking surface area of 2.98 km^2 and a reduced volume of 13.539×10^6 m^3 based on 415 survey points. Rather, it demonstrates that the lake's total capacity is highly sensitive to the operating threshold of the western outlet dam at the time of acoustic logging, as well as the spatial density of survey points employed. Surveying conducted during high pool levels tends to capture an inflated water column profile, which may overestimate true long-term storage capacity. Nevertheless, the ongoing loss of physical deep-water storage capacity due to watershed degradation remains a critical concern. As identified through Revised Universal Soil Loss Equation (RUSLE) modeling, intensive human land-use changes — specifically the proliferation of unengineered rural roads and terrace farming on steep, fragile slopes — have significantly accelerated soil erosion within the watershed. The resultant sediment load is transported primarily via the Syankhudi and Talbesi feeder streams, forming expanding underwater deltas at the lake inlets. Current bathymetric profiles confirm this phenomenon, showing localized swallowing and rising bed elevations precisely at the northern feeder stream inlets where deltaic pro-gradation is most active. Collectively, these findings reinforce the urgent need for integrated watershed management strategies to arrest further physical degradation of the Begnas Lake basin.

Table 9: Morphological Characteristics of Rupa Lake

Morphometric Parameter	Unit	Current Studies	Baseline	Difference
Maximum Depth	m	4.68	6	1.32
Mean Depth	m	2.86	3	0.14
Total Lake Area	sq km	1.02	1.22	1.92
Volume	m^3	$2.91*10^6$	$2.26*10^6$	$0.65*10^6$

*Note: Bathymetric Data from Rupa Tal Integrated Development Project in 2017 is taken as baseline data,

The data and information from the Table 9 draws following notable observations

- **Maximum depth** shows the largest relative decline — the current survey value of 4.68 m is only 78% of the 6.0 m baseline, representing the most significant proportional loss among all parameters.
- **Total lake area** has also contracted considerably, with the current 1.02 sq km standing at roughly 84% of the 1.22 sq km baseline.
- **Mean depth** shows a comparatively modest reduction, with current values very close to the baseline.
- **Volume**, interestingly, shows the current study recording a higher value (2.91×10^6 m^3) than the baseline (2.26×10^6 m^3), likely reflecting differences in survey timing relative to dam operations

or water levels, as discussed in the morphometric analysis. Volume increment is due to variation in calculation process and also Eco sounding was not used by RTIDP in 2017.

Table 10: Sedimentation Rate and Watershed Soil Loss Estimates for Rupa Lake (2017–2025/26)

INDICATOR	VALUE
SURVEY PERIOD	2017 – 2025/26
INTER-SURVEY INTERVAL	~8 years
TOTAL LAKE AREA LOSS	19.2 Ha (15.7% of baseline)
ANNUAL LAKE AREA LOSS	2.4 Ha/year
ANNUAL MEAN DEPTH LOSS	1.75 cm/year
ESTIMATED ANNUAL SEDIMENT VOLUME	~68,640 m^3/year
ESTIMATED ANNUAL SEDIMENT MASS	~89,232 t/year
WATERSHED AREA	2,663 Ha
MEAN SOIL LOSS RATE	**~33.5 t/ha/year**

Comparative analysis of the 2017 baseline and the current 2025/26 bathymetric survey, as in Table 10 indicates that Rupa Lake has lost approximately 19.2 Ha of its surface extent over eight years, with mean depth declining by 0.14 m over the same period. These changes correspond to an estimated annual sediment accumulation of approximately 68,640 m^3, or roughly 89,232 tonnes per year when converted using a standard lacustrine bulk dry density of 1.3 t/m^3. Distributed across the 2,663 Ha Watershed, this yields a mean soil loss rate of approximately 33.5 t/ha/year. It is noted that the apparent increase in water volume between the two surveys is attributed to differences in seasonal water levels and dam operations at the time of each survey, rather than any genuine morphological improvement, and has therefore not been used in the sedimentation rate derivation.

A soil loss rate of 33.5 t/ha/year falls within the very high erosion severity category under FAO and USLE-based classification frameworks, where losses exceeding 10 t/ha/year are considered high and those approaching 40 t/ha/year are classified as severe. This is consistent with the steep terrain, intense monsoonal precipitation, progressive land-use change, and documented road-induced erosion that characterize the Rupa Lake watershed (RTCIDP, 2017). It should be noted that this figure represents a watershed-averaged, lake-trapped estimate and therefore constitutes a conservative lower bound, as sediment exported through the lake outlet is not captured in the morphometric comparison. These findings reinforce the need for integrated watershed management measures to complement any in-lake restoration works, as sedimentation will continue to offset dredging benefits unless upstream sediment sources are concurrently addressed.

Chapter 7. Conclusions and Recommendations

7.1 Conclusions

This bathymetric survey and sedimentation assessment of Begnas and Rupa Lakes provides a comprehensive and updated characterisation of the morphometric condition and sediment dynamics of both water bodies in the Pokhara Valley. The findings confirm that both lakes are undergoing progressive physical deterioration driven by sedimentation, watershed degradation, and anthropogenic land-use pressures, albeit at markedly different rates and stages of severity.

7.1.1 Begnas Lake

Begnas Lake retains comparatively greater hydrological resilience by virtue of its larger basin dimensions, recording a current surface area of 305.6 Ha, a maximum depth of 11.64 m, a mean depth of 7.49 m, and a total storage volume of 22.74×10^6 m³. However, the long-term volumetric record presents an unambiguous trajectory of decline. Total storage capacity has fallen from 29.05 million m³ in 1992 to 22.74 million m³ in the current survey — a cumulative loss of approximately 6.31 million m³ over three decades. Critically, the rate of volumetric loss has accelerated substantially: the annual sedimentation rate between 1992 and 1994 was approximately 63,500 m³/year, whereas between 1994 and 2026 this rate increased nearly threefold to approximately 193,200 m³/year. This acceleration is consistent with the documented intensification of land-use pressures within the 1,821 Ha watershed, particularly the proliferation of unengineered rural roads and agricultural encroachment on steep slopes. The resultant sediment load is conveyed primarily via the Syankhudi and Talbesi feeder streams, with bathymetric profiles confirming the formation of expanding underwater deltas at the northern lake inlets.

7.1.2 Rupa Lake

Rupa Lake presents a more acute and immediate concern. The current survey records a surface area of 102.8 Ha, a maximum depth of 4.68 m, a mean depth of 2.86 m, and a total volume of 2.91×10^6 m³. When compared against the 2017 RTCIDP baseline, the lake has lost 19.2 Ha of its surface extent — a contraction of 15.7% in eight years — and maximum depth has declined by 1.32 m, representing a 22% proportional reduction. These morphometric changes correspond to an estimated annual sediment accumulation of approximately 68,640 m³/year, equivalent to an annual sediment mass of approximately 89,232 tonnes. Distributed across the 2,663 Ha watershed, this yields a mean soil loss rate of approximately 33.5 t/ha/year, classified as very high under FAO and USLE-based erosion severity frameworks. The Talbesi Khola river, with documented riverbed aggradation of up to 3 metres at the lake inlet, represents the dominant sediment delivery pathway. The shallow, bathymetrically constrained basin geometry of Rupa Lake renders it particularly vulnerable to continued infilling, eutrophication, and eventual ecological collapse if current trends persist.

7.1.3 Comparative Assessment

While Begnas Lake currently retains greater volumetric and morphometric resilience, both lakes are on trajectories of long-term physical degradation that will progressively compromise their ecological function, water storage capacity, fisheries productivity, and socioeconomic value to dependent communities. The accelerating sedimentation rates documented in both systems reflect a shared underlying driver: the intensification of erosive land-use practices within their respective watersheds in the absence of adequate watershed management. Periodic bathymetric monitoring has proven essential in detecting and quantifying these changes, and the present survey establishes an updated baseline against which future assessments can be benchmarked.

7.2 Recommendations

7.2.1 Integrated Watershed Management

The most critical and urgent intervention required for both lakes is the implementation of integrated watershed management programmes targeting the primary sources of sediment generation within their watersheds. Specific measures should include the stabilisation and drainage improvement of unengineered rural road networks, which have been identified as disproportionate contributors to watershed erosion; reforestation and revegetation of degraded hillslopes, particularly in areas of high erosion potential adjacent to the feeder stream corridors; and the construction of sediment trapping structures — including check dams and debris basins — at strategic locations along the Talbesi Khola and Syankhudi streams prior to their entry into the lake systems. Agricultural practices on steep marginal slopes should be regulated and supported with appropriate soil conservation measures, including contour bunding, bench terracing, and cover cropping.

7.2.2 In-Lake Sediment Management

For Rupa Lake in particular, the estimated in-lake sediment stock of approximately 1,343,828 m³ with a solid mass of around 2 million metric tonnes warrants serious consideration of mechanical dredging as a restoration intervention. However, dredging should only be undertaken in conjunction with upstream watershed management, as ongoing watershed-derived sediment loading at the current rate of approximately 68,640 m³/year will progressively negate any volumetric gains achieved through in-lake sediment removal. Pre-dredging assessment should include sediment core analysis to characterise nutrient content, contaminant loading, and historical accumulation rates, in order to inform both the dredging design and the safe disposal or beneficial reuse of extracted material.

7.2.3 Bathymetric Monitoring Programme

A programme of periodic bathymetric surveys should be instituted for both lakes at intervals not exceeding five years. Surveys should be conducted under standardised hydrological conditions — ideally at a consistent seasonal water level relative to the regulatory dam threshold — to ensure comparability across survey periods and to eliminate the confounding effects of water level variability on volumetric estimates. The RTK-GNSS and single-beam echo sounder methodology employed in the present survey is recommended as the standard approach, with survey grids and data processing protocols documented and archived to facilitate direct inter-survey comparison.

7.2.4 Policy and Institutional Coordination

The findings of this survey should be formally communicated to the relevant government bodies, including the Department of Hydrology and Meteorology, the Department of Soil Conservation and Watershed Management, and the respective local governments of Pokhara Metropolitan City and Rupa Rural Municipality, to inform evidence-based lake and watershed policy. Institutional coordination between these bodies is essential to ensure that watershed management interventions are implemented in a timely and spatially coherent manner. Long-term legal protection of the lake watersheds through land-use zoning and environmental safeguard provisions is strongly recommended to prevent further encroachment and degradation.

7.2.5 Community Engagement and Awareness

Given the direct dependence of local communities on both lakes for fisheries, irrigation, domestic water supply, and tourism, community-based lake monitoring and watershed stewardship programmes should be established and supported. Engagement with local stakeholders — including fishing cooperatives, agricultural users, and tourism operators — will be essential to ensure the long-term sustainability and ownership of conservation interventions, and to provide ground-level intelligence on emerging sedimentation and pollution pressures that may not be captured by periodic technical surveys alone.

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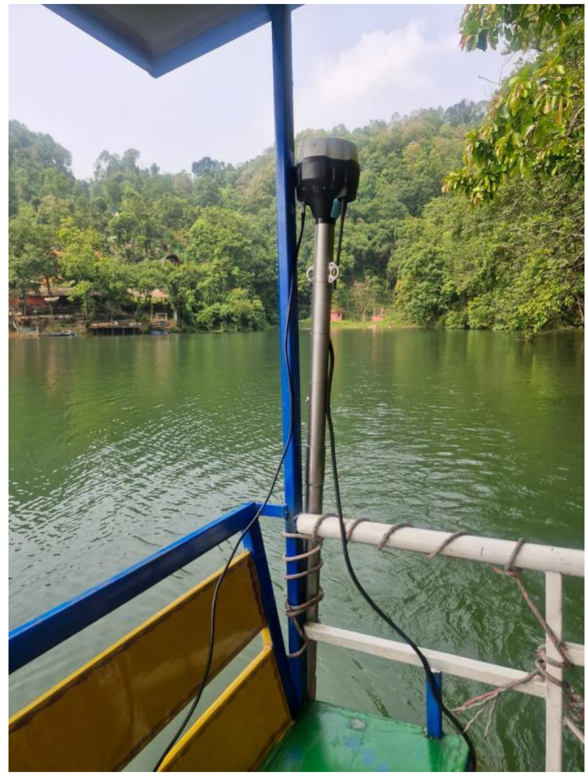
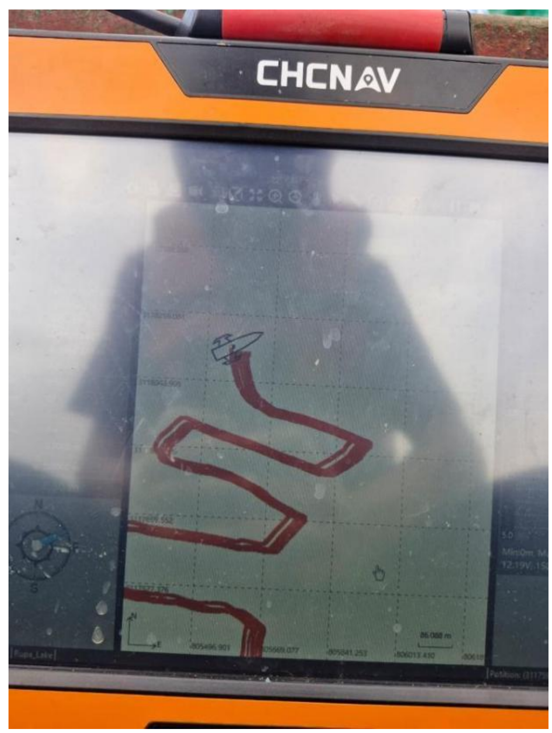
ANNEXES

Field Photographs




CHCNAV

Specification of D390 echosounder

SPECIFICATIONS

Measurement Parameters	
Frequency	200 kHz
Output power	500 W RMS max
Depth range	0.15 m to 300 m
Accuracy	± 0.01 m + 0.1% of depth
Resolution	0.01 m
Sampling rate	Up to 60 Hz
Draft adjustment	0 m to 9.9 m
Sound velocity adjustment	1300 m/s to 1700 m/s
Data output	- User defined - CHCNAV - NMEA SDDPT/SDDBT - Original Waveform
Display	12-inch resistive touch screen
LCD resolution	HD 1024 × 768 pixels
Interface	- 2 x RS-232 serial ports - 2 x USB 3.0 ports - 2 x USB 2.0 ports
RAM	4 GB DDR 3L 1600 MHz
ROM	32 GB
CPU	1.6 GHz
Power consumption	25 W

Physical	
Size (L x W x H)	36.5 cm x 25.8 cm x 0.95 cm
Weight	4.7 kg
Pulse power	300 W
Input power	10 V DC to 30 V DC
Operating temperature	-30°C to +60°C (-22F° to +140°F)
Ingress protection	IP66

*Specifications are subject to change without notice.

Specifications of EMLID REACH RS2

Mechanical

- • Dimensions126x126x142 mm
- • Weight950 g
- • Operating tº-20…+65 ºC
- • Ingress protectionIP67

Electrical

- • Autonomy16 hrs as 3.5G RTK rover, 22 hrs logging
- • BatteryLiFePO4 6400 mAh, 6.4 V
- • External power input6–40 V
- • ChargingUSB Type-C 5 V, 2 A
- • CertificationFCC, CE

Positioning

- • StaticH: 4mm+0.5ppm
- • PPKH: 5mm+0.5ppm
- • RTKH: 7mm+1ppm
- • Convergence time~5 s typically

Connectivity

- • LoRa radio
- • Frequency range868/915 MHz
- • Power0.1 W
- • DistanceUp to 8 km
- • 3.5G modem
- • RegionsGlobal
- • BandsQuad-band, 850/1900, 900/1800 MHz
- • SIM cardNano-SIM
- • Wi-Fi802.11b/g/n
- • Bluetooth4.0/2.1 EDR
- • PortsRS-232, USB Type-C

Data

- • CorrectionsNTRIP, RTCM3
- • Position outputNMEA, LLH/XYZ
- • Data loggingRINEX with events with update rate up to 20 Hz
- • Internal storage16 GB 160+ days of logging at 1 Hz

GNSS

- • Signal trackedGPS/QZSS L1C/A, L2C GLONASS L1OF, L2OF BeiDou B1I, B2I Galileo E1-B/C, E5b
- • Number of channels184
- • Update rates20 Hz GPS / 5 Hz GNSS
- • IMU9DOF

Sample Raw Data from the Hydrosurvey (This is just sample, whole data is submitted seperatly in excel file)

Name	Time	Lat	Lon	Water Level	HighDepth	Elevation	HighRelativeDepth	LowRelativeDepth	HighSeabedElevation	LowSeabedElevation	HighSeabedHeight	LowSeabedHeight	MudThickne	Speed
gj000001	10:23.0	28°09′57.895332″N	84°05′36.855480″E	680.724	2.26	678.464	-678.46	-680.72	678.464	680.724	630.659	632.919	-2.26	0.04
gj000002	10:24.0	28°09′57.896442″N	84°05′36.855228″E	680.728	2.28	678.448	-678.45	-680.73	678.448	680.728	630.643	632.923	-2.28	0.03
gj000003	10:25.0	28°09′57.897612″N	84°05′36.855072″E	680.713	2.35	678.363	-678.36	-680.71	678.363	680.713	630.558	632.908	-2.35	0.06
gj000004	10:26.0	28°09′57.898866″N	84°05′36.854892″E	680.713	2.38	678.333	-678.33	-680.71	678.333	680.713	630.528	632.908	-2.38	0.03
gj000005	10:27.0	28°09′57.900162″N	84°05′36.854610″E	680.709	2.39	678.319	-678.32	-680.71	678.319	680.709	630.514	632.904	-2.39	0.03
gj000006	10:28.0	28°09′57.901446″N	84°05′36.853734″E	680.721	2.4	678.321	-678.32	-680.72	678.321	680.721	630.516	632.916	-2.4	0.06
gj000007	10:29.0	28°09′57.903318″N	84°05′36.852888″E	680.715	2.39	678.325	-678.33	-680.72	678.325	680.715	630.52	632.91	-2.39	0.05
gj000008	10:30.0	28°09′57.904680″N	84°05′36.851916″E	680.731	2.39	678.341	-678.34	-680.73	678.341	680.731	630.536	632.926	-2.39	0.06
gj000009	10:31.0	28°09′57.906342″N	84°05′36.851106″E	680.705	2.4	678.305	-678.31	-680.71	678.305	680.705	630.5	632.9	-2.4	0.03

gj000010	10:32.0	28°09′57.907866″N	84°05′36.850332″E	680.709	2.45	678.259	-678.26	-680.71	678.259	680.709	630.454	632.904	-2.45	0.06
gj000011	10:33.0	28°09′57.909450″N	84°05′36.849474″E	680.707	2.45	678.257	-678.26	-680.71	678.257	680.707	630.452	632.902	-2.45	0.05
gj000012	10:34.0	28°09′57.910920″N	84°05′36.848772″E	680.735	2.45	678.285	-678.29	-680.74	678.285	680.735	630.48	632.93	-2.45	0.08
gj000013	10:35.0	28°09′57.912456″N	84°05′36.848046″E	680.746	2.46	678.286	-678.29	-680.75	678.286	680.746	630.481	632.941	-2.46	0.06
gj000014	10:36.0	28°09′57.914598″N	84°05′36.846720″E	680.746	2.56	678.186	-678.19	-680.75	678.186	680.746	630.381	632.941	-2.56	0.06
gj000015	10:37.0	28°09′57.917022″N	84°05′36.844860″E	680.753	2.59	678.163	-678.16	-680.75	678.163	680.753	630.358	632.948	-2.59	0.08
gj000016	10:38.0	28°09′57.920796″N	84°05′36.842556″E	680.717	2.59	678.127	-678.13	-680.72	678.127	680.717	630.322	632.912	-2.59	0.11
gj000017	10:39.0	28°09′57.924336″N	84°05′36.839802″E	680.74	2.56	678.18	-678.18	-680.74	678.18	680.74	630.375	632.935	-2.56	0.15
gj000018	10:40.0	28°09′57.928638″N	84°05′36.836274″E	680.73	2.62	678.11	-678.11	-680.73	678.11	680.73	630.305	632.925	-2.62	0.17
gj000019	10:41.0	28°09′57.933078″N	84°05′36.832584″E	680.734	2.7	678.034	-678.03	-680.73	678.034	680.734	630.23	632.93	-2.7	0.17
gj000020	10:42.0	28°09′57.937764″N	84°05′36.828624″E	680.736	2.71	678.026	-678.03	-680.74	678.026	680.736	630.222	632.932	-2.71	0.21

gj000021	10:43.0	28°09′57.943614″N	84°05′36.824700″E	680.759	2.73	678.029	-678.03	-680.76	678.029	680.759	630.225	632.955	-2.73	0.17
gj000022	10:44.0	28°09′57.949776″N	84°05′36.820200″E	680.738	2.78	677.958	-677.96	-680.74	677.958	680.738	630.154	632.934	-2.78	0.23
gj000023	10:45.0	28°09′57.956478″N	84°05′36.815574″E	680.73	2.81	677.92	-677.92	-680.73	677.92	680.73	630.116	632.926	-2.81	0.25
gj000024	10:46.0	28°09′57.963414″N	84°05′36.810828″E	680.738	2.9	677.838	-677.84	-680.74	677.838	680.738	630.034	632.934	-2.9	0.27
gj000025	10:47.0	28°09′57.970500″N	84°05′36.805842″E	680.745	2.97	677.775	-677.78	-680.75	677.775	680.745	629.971	632.941	-2.97	0.26
gj000026	10:48.0	28°09′57.977952″N	84°05′36.800292″E	680.753	3.05	677.703	-677.7	-680.75	677.703	680.753	629.899	632.949	-3.05	0.27
gj000027	10:49.0	28°09′57.985602″N	84°05′36.794292″E	680.736	3.09	677.646	-677.65	-680.74	677.646	680.736	629.842	632.932	-3.09	0.31
gj000028	10:50.0	28°09′57.993288″N	84°05′36.788538″E	680.765	3.07	677.695	-677.7	-680.77	677.695	680.765	629.891	632.961	-3.07	0.32
gj000029	10:51.0	28°09′58.001322″N	84°05′36.782562″E	680.778	3.11	677.668	-677.67	-680.78	677.668	680.778	629.864	632.974	-3.11	0.23
gj000030	10:52.0	28°09′58.008966″N	84°05′36.776484″E	680.802	3.15	677.652	-677.65	-680.8	677.652	680.802	629.848	632.998	-3.15	0.24
gj000031	10:53.0	28°09′58.016940″N	84°05′36.770418″E	680.796	3.15	677.646	-677.65	-680.8	677.646	680.796	629.842	632.992	-3.15	0.32

gj000032	10:54.0	28°09'58.025748"N	84°05'36.763866"E	680.806	3.21	677.596	-677.6	-680.81	677.596	680.806	629.792	633.002	-3.21	0.31
gj000033	10:55.0	28°09'58.034514"N	84°05'36.757806"E	680.829	3.24	677.589	-677.59	-680.83	677.589	680.829	629.785	633.025	-3.24	0.31
gj000034	10:56.0	28°09'58.044396"N	84°05'36.751662"E	680.806	3.21	677.596	-677.6	-680.81	677.596	680.806	629.792	633.002	-3.21	0.3
gj000035	10:57.0	28°09'58.054476"N	84°05'36.746022"E	680.823	3.25	677.573	-677.57	-680.82	677.573	680.823	629.769	633.019	-3.25	0.33
gj000036	10:58.0	28°09'58.064304"N	84°05'36.739956"E	680.819	3.25	677.569	-677.57	-680.82	677.569	680.819	629.765	633.015	-3.25	0.34
gj000037	10:59.0	28°09'58.074456"N	84°05'36.733734"E	680.803	3.2	677.603	-677.6	-680.8	677.603	680.803	629.8	633	-3.2	0.35
gj000038	11:00.0	28°09'58.085118"N	84°05'36.728334"E	680.807	3.29	677.517	-677.52	-680.81	677.517	680.807	629.714	633.004	-3.29	0.34
gj000039	11:01.0	28°09'58.096056"N	84°05'36.722664"E	680.792	3.29	677.502	-677.5	-680.79	677.502	680.792	629.699	632.989	-3.29	0.38
gj000040	11:02.0	28°09'58.106946"N	84°05'36.716784"E	680.769	3.31	677.459	-677.46	-680.77	677.459	680.769	629.656	632.966	-3.31	0.45
gj000041	11:03.0	28°09'58.118184"N	84°05'36.711144"E	680.768	3.35	677.418	-677.42	-680.77	677.418	680.768	629.615	632.965	-3.35	0.33
gj000042	11:04.0	28°09'58.129434"N	84°05'36.705786"E	680.781	3.33	677.451	-677.45	-680.78	677.451	680.781	629.648	632.978	-3.33	0.35

gj000 043	11:0 5.0	28°09′58. 141374″N	84°05′36. 700950″E	680.7 73	3.39	677.383	-677.38	-680.77	677.38 3	680.773	629.58	632.97	-3.39	0.34
gj000 044	11:0 6.0	28°09′58. 153218″N	84°05′36. 695316″E	680.7 81	3.42	677.361	-677.36	-680.78	677.36 1	680.781	629.558	632.978	-3.42	0.35
gj000 045	11:0 7.0	28°09′58. 165272″N	84°05′36. 690606″E	680.7 94	3.34	677.454	-677.45	-680.79	677.45 4	680.794	629.651	632.991	-3.34	0.44
gj000 046	11:0 8.0	28°09′58. 178178″N	84°05′36. 686280″E	680.7 77	3.32	677.457	-677.46	-680.78	677.45 7	680.777	629.654	632.974	-3.32	0.38
gj000 047	11:0 9.0	28°09′58. 191816″N	84°05′36. 682338″E	680.7 87	3.4	677.387	-677.39	-680.79	677.38 7	680.787	629.584	632.984	-3.4	0.43
gj000 048	11:1 0.0	28°09′58. 206330″N	84°05′36. 678894″E	680.7 87	3.42	677.367	-677.37	-680.79	677.36 7	680.787	629.565	632.985	-3.42	0.53
gj000 049	11:1 1.0	28°09′58. 220580″N	84°05′36. 675264″E	680.8	3.42	677.38	-677.38	-680.8	677.38	680.8	629.578	632.998	-3.42	0.41
gj000 050	11:1 2.0	28°09′58. 235142″N	84°05′36. 671526″E	680.8	3.43	677.37	-677.37	-680.8	677.37	680.8	629.568	632.998	-3.43	0.46
gj000 051	11:1 3.0	28°09′58. 249614″N	84°05′36. 667212″E	680.8 03	3.42	677.383	-677.38	-680.8	677.38 3	680.803	629.581	633.001	-3.42	0.45
gj000 052	11:1 4.0	28°09′58. 264044″N	84°05′36. 662052″E	680.7 93	3.43	677.363	-677.36	-680.79	677.36 3	680.793	629.561	632.991	-3.43	0.5
gj000 053	11:1 5.0	28°09′58. 278534″N	84°05′36. 656634″E	680.7 93	3.48	677.313	-677.31	-680.79	677.31 3	680.793	629.511	632.991	-3.48	0.47

gj000 054	11:1 6.0	28°09′58. 292610″N	84°05′36. 651060″E	680.7 86	3.49	677.296	-677.3	-680.79	677.29 6	680.786	629.494	632.984	-3.49	0.44
gj000 055	11:1 7.0	28°09′58. 307046″N	84°05′36. 645048″E	680.7 78	3.48	677.298	-677.3	-680.78	677.29 8	680.778	629.496	632.976	-3.48	0.51
gj000 056	11:1 8.0	28°09′58. 321968″N	84°05′36. 638874″E	680.7 9	3.48	677.31	-677.31	-680.79	677.31	680.79	629.508	632.988	-3.48	0.42
gj000 057	11:1 9.0	28°09′58. 336848″N	84°05′36. 632208″E	680.8 11	3.5	677.311	-677.31	-680.81	677.31 1	680.811	629.51	633.01	-3.5	0.45
gj000 058	11:2 0.0	28°09′58. 351758″N	84°05′36. 625572″E	680.8 13	3.49	677.323	-677.32	-680.81	677.32 3	680.813	629.522	633.012	-3.49	0.45
gj000 059	11:2 1.0	28°09′58. 366644″N	84°05′36. 618456″E	680.8 38	3.52	677.318	-677.32	-680.84	677.31 8	680.838	629.517	633.037	-3.52	0.51
gj000 060	11:2 2.0	28°09′58. 381434″N	84°05′36. 611118″E	680.8 29	3.55	677.279	-677.28	-680.83	677.27 9	680.829	629.478	633.028	-3.55	0.53
gj000 061	11:2 3.0	28°09′58. 396356″N	84°05′36. 603630″E	680.8 39	3.56	677.279	-677.28	-680.84	677.27 9	680.839	629.478	633.038	-3.56	0.46
gj000 062	11:2 4.0	28°09′58. 410678″N	84°05′36. 595854″E	680.8 44	3.61	677.234	-677.23	-680.84	677.23 4	680.844	629.433	633.043	-3.61	0.49
gj000 063	11:2 5.0	28°09′58. 425696″N	84°05′36. 588144″E	680.8 76	3.6	677.276	-677.28	-680.88	677.27 6	680.876	629.475	633.075	-3.6	0.58
gj000 064	11:2 6.0	28°09′58. 441578″N	84°05′36. 579612″E	680.8 67	3.58	677.287	-677.29	-680.87	677.28 7	680.867	629.486	633.066	-3.58	0.57

gj000065	11:27.0	28°09’58.457400”N	84°05’36.570774”E	680.869	3.55	677.319	-677.32	-680.87	677.319	680.869	629.518	633.068	-3.55	0.55
gj000066	11:28.0	28°09’58.472814”N	84°05’36.561678”E	680.86	3.58	677.28	-677.28	-680.86	677.28	680.86	629.48	633.06	-3.58	0.58
gj000067	11:29.0	28°09’58.487988”N	84°05’36.552096”E	680.859	3.52	677.339	-677.34	-680.86	677.339	680.859	629.539	633.059	-3.52	0.54
gj000068	11:30.0	28°09’58.503210”N	84°05’36.542412”E	680.882	3.54	677.342	-677.34	-680.88	677.342	680.882	629.542	633.082	-3.54	0.6
gj000069	11:31.0	28°09’58.519560”N	84°05’36.532596”E	680.826	3.56	677.266	-677.27	-680.83	677.266	680.826	629.466	633.026	-3.56	0.47
gj000070	11:32.0	28°09’58.534926”N	84°05’36.522444”E	680.808	3.55	677.258	-677.26	-680.81	677.258	680.808	629.458	633.008	-3.55	0.61