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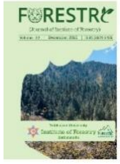

Original research article

Morphometry and sedimentation of Kupinde lake and its watershed in Salyan District, Nepal

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A R T I C L E I N F O

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A B S T R A C T

Kupinde Lake (elevation: 1,160 m; area: 0.25 km^2) is a mid-hill lake located in the Salyan district of Nepal. It serves as an important source of water for the surrounding regions and downstream communities. This study examines the lake morphometry watershed dynamics and sedimentation in Kupinde Lake. A bathymetric survey was conducted using a depth sounder in 2023. The results show that the lake has a maximum depth of 37 m with a total volume of 6.14 million m^3. Within the watershed, between 2009 and 2024, forest cover declined by 6.2%, barren land expanded by 60.5%, agricultural land increased by 1.2% and water bodies enlarged by 17.4%. Annual soil loss was estimated at 36,821 t yr^{-1} (equivalent to 25,394 m^3 yr^{-1}), with the highest contributions originating from agricultural land and barren areas, while forested zones exhibited the lowest erosion rates. Over time, soil erosion from agricultural and barren lands has accelerated sedimentation, contributing to gradual lake infilling and altering its morphology. These changes can affect habitat availability, nutrient cycling and water quality, underlining the importance of continuous monitoring and integrated watershed management to mitigate erosion, sustain water resources and preserve ecosystem integrity. This study provides essential baseline data for the conservation and management of Kupinde lake under growing anthropogenic and climatic.

INTRODUCTION

Lakes are among the most dynamic ecosystems on Earth, functioning as natural reservoirs of water, biodiversity and cultural heritage (Heino et al., 2021). Globally, lakes store an estimated 181,900 km^3 of water (Messager et al., 2016), support countless species and serve as crucial regulators of hydrological and biogeochemical cycles (Downing, 2010). Yet, these fragile systems are under a growing threat from accelerated sedimentation, changing morphometry and anthropogenic stressors (Owens, 2020). Excessive sediment deposition is now recognized as one of the primary drivers of ecosystem degradation in lakes worldwide, reducing water depth, altering habitat structure, and disrupting nutrient and oxygen balances (Mitsch et al., 2015). Such processes are particularly alarming in high-altitude regions like the Himalayas, where lakes are not only ecologically significant but also culturally and economically indispensable (Khadka et al., 2025). Sedimentation and lake morphology are closely intertwined, serving as important indicators of ecological health (Schallenberg et al., 2013). Sedimentation reflects both natural processes, such as erosion, hydrodynamics and organic matter deposition, and human-induced pressures, including deforestation, road construction and agricultural expansion (Ma et al., 2010). Morphometric features such as depth, surface area and shoreline complexity further regulate these dynamics by influencing hydro-chemical parameters, water circulation and trophic state variables (Liu et al., 2011; Nõges et al., 2003). In turn, changes in lake morphology often alter ecological interactions, including species

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composition, productivity and resilience to disturbances (Heino et al., 2021; Mori et al., 2013).

Within the Himalayan region, lakes are particularly sensitive to internal and external drivers. Rapid warming trends, glacial retreat, watershed degradation and increasing precipitation variability are reshaping lake hydrology and sedimentation regimes. Recent studies from Nepal highlight these dynamics, including wetland and watershed changes in Pokhara Valley (Sigdel et al., 2025), land-use change and sediment-related hazards in the Phewa watershed (Vuillez et al., 2018), and accelerated shrinkage of the Phewa Lake due to increased sediment influx (Watson et al., 2019). Similarly, climate change impacts on glaciers and glacial lakes across the Nepal Himalayas have been well documented (Khadka et al., 2023). Human activities compound these effects: road networks fragment catchments, agricultural runoff enhances nutrient loading, and tourism introduces invasive species and chemical contaminants (Ogidi & Akpan, 2022; Okorondu et al., 2022). As integral wetland systems, lakes provide critical ecosystem services such as water storage, flood regulation, carbon sequestration and biodiversity conservation. Studies highlight their global importance (Bassi et al., 2014; Ye et al., 2022) as well as regional significance in the central Himalayas, including the transboundary Karnali River Basin (Shrestha et al., 2019), underscoring the urgency of their conservation. Kupinde Lake, exemplifies the ecological and cultural significance. As one of the largest natural lakes in the province, alongside Rara, Phokshundo, Baraha Tal and Shyarpu, Kupinde Lake represents an essential freshwater resource. It holds religious importance, attracts thousands of domestic tourists and sustains local livelihoods. Recent hydrochemical assessments emphasize its ecological value by linking water quality parameters to amphibian abundance and broader biodiversity (Sunar et al., 2022).

Despite its importance, Kupinde Lake remains insufficiently studied. Existing research has primarily focused on physicochemical water quality, biodiversity and localised landslide impacts (Rawal & Joshi, 2022; Sunar et al., 2022), while its geomorphological dynamics, sedimentation processes and land-use changes within its watershed remain poorly understood. Most sedimentation studies conducted in Nepalese lakes are either site-specific or focused on well-known systems such as Rara and Phewa, leaving other mid-hill and subtropical lakes underrepresented (Thakuri et al., 2021). This gap is particularly concerning, as lakes such as Kupinde are increasingly exposed to anthropogenic stressors. For example, the recent road construction has improved accessibility around Kupinde Lake; however, studies elsewhere indicate that such developments can increase risks of sediment influx, road salt contamination and introduction of invasive species (Merz et al., 2014; Rawal and Joshi, 2022; Schuler and Relyea, 2018). Notably, comprehensive baseline information is needed to assess ecosystem health, predict future risks and guide conservation measures for Kunpinde Lake. Furthermore, global research shows that lake morphometry strongly influences sediment deposition and nutrient cycling (Liu et al., 2011; Nõges et al., 2003). Yet, for Kupinde Lake, no systematic bathymetric survey and sedimentation study has been undertaken. Similarly, while Himalayan wetlands are often studied as paleoenvironmental indicators of climate and land-use change (Gopal et al., 2010; Thakuri et al., 2021), such records are absent for Kupinde Lake. This not only limits ecological understanding, but also hinder evidence-based policymaking for lake watershed planning and management.

The present study aims to investigate the morphological characteristics of Kupinde Lake and examine sedimentation dynamics, thereby addressing the existing gaps in our understanding of its hydrological and ecological processes. A detailed bathymetric profile is generated to describe the morphometric features of the lake, providing insights into its depth variations, and overall structure and volume. In addition, sedimentation processes and erosion patterns within the watershed is assessed to understand the sources and movement of sediments contributing to lake infilling. This study also evaluates the land use and land cover (LULC) changes over time, examining their implications for sediment input and watershed degradation. Furthermore, the research establishes essential baseline data that can support long-term ecological monitoring and guide sustainable watershed management strategies.

The study contributes significantly to both scientific understanding and practical management of the Himalayan lakes. Scientifically, it addresses gaps in Himalayan limnology by examining sedimentation dynamics and morphometric characteristics in underexplored mid-hill regions. By integrating geomorphological and land-use analyses, it provides a comprehensive understanding of how lake morphometry and watershed processes influence sediment deposition and water quality, offering valuable comparative data for global studies on lake ecology. Practically, the research generates essential baseline information for the sustainable management and conservation of Kupinde Lake, which faces increasing pressures from tourism, development and land-use changes. Furthermore, the findings support strategies to mitigate eutrophication, biodiversity loss and ecosystem degradation, while guiding evidence-based watershed management, wetland conservation, climate adaptation and sustainable tourism planning. Such strategies will be beneficial to inform local and regional policymakers to strongly promote the long-term ecological sustainability of the Himalayan lake systems.

MATERIALS AND METHODS

Study area

Kupinde lake, located in Salyan District in Karnali Province, Nepal, is a natural freshwater, subtropical mid-hill tectonic lake that serves as both an ecological hotspot and a culturally significant site (Figure 1). It lies within the mid-hill region of the Nepal Himalayas. The lake is renowned for its scenic beauty and its role in supporting aquatic and terrestrial biodiversity. It holds cultural and spiritual importance for indigenous communities in Bangad Kupinde Municipality, being integral to local traditions, rituals and festivals. Visitors to Kupinde Lake can enjoy stunning views of the lake itself and the surrounding hills and forests. Its ecological significance is closely linked to its watershed, which spans approximately 9.75 km^2 and is composed of agricultural land, barren land, forest cover and settlements. The lake acts as a critical water reservoir during dry periods, sustaining local agriculture and contributing to the livelihoods of communities dependent on its resources (Dhital, 2015). Understanding the lake's morphological dynamics and sedimentation patterns is, therefore, essential for evaluating its ecological health and informing effective conservation strategies.

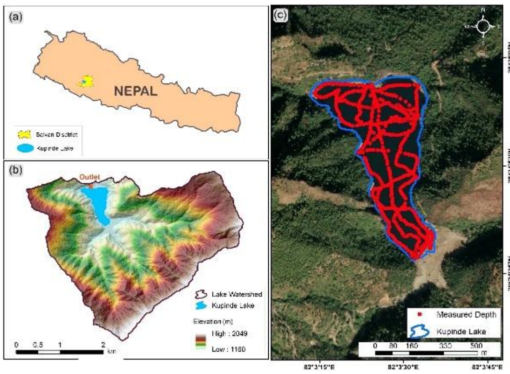

Figure 1. Study site: (a) Location of Kupinde lake in Nepal, (b) Kupinde lake and its watershed shown on an elevation map, (c) Surveyed points for depth measurements within the lake

Kupinde Lake is situated at an altitude of approximately 1,160 m above sea level and covers an area of 0.25 km^2 (CODEFUND, 2017). The lake extends roughly 1,250 m in length and 250 m in width, with a maximum reported depth of approximately 48 m (CODEFUND, 2017). Salyan District encompasses a total area of 1,462 km^2 and exhibits a subtropical to temperate climate, with average annual rainfall of 1,100 mm, maximum temperature reaching 31 °C during summer and minimum temperature around 3 °C during winter (Rawal & Joshi, 2022). The study area has experienced road construction through steep and fragile terrain, leading to slope destabilization, increased landslide risk and soil erosion, which affect both environmental stability and local communities (Sunar et al., 2022).

This study employed a combination of field surveys, remote sensing and Geographic Information System (GIS)-based modelling to investigate the bathymetry, sedimentation and watershed dynamics of Kupinde Lake. The methodology was designed to quantify lake morphology, estimate water volume, analyse LULC changes, and estimate soil erosion within the Kupinde watershed. A schematic representation of the methodological workflow is shown in Figure 2.

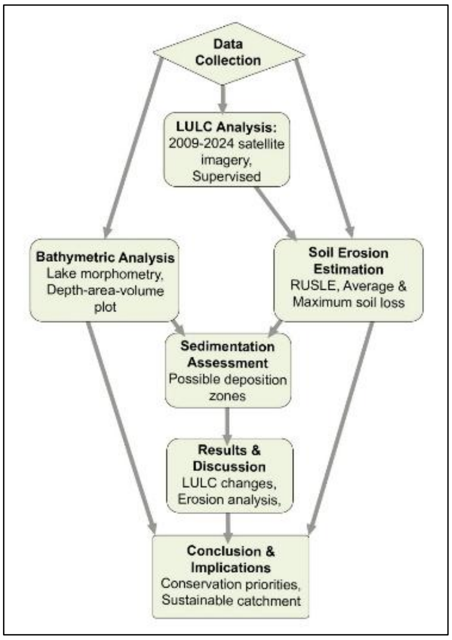

Figure 2. Methodological framework of the study

Data source

Multiple datasets were utilised to capture both spatial and temporal aspects of the lake and its watershed. The details of the data sources, types, temporal coverage and purpose are summarised in Table 1.

Table 1. Data sources and their purposes

Data Type	Collection Period	Purpose	Source
Depth of Lake	Jan 14 2023	Map lake bathymetry	Field survey using HDR 650 Humminbird® depth sounder and Garmin GPS 64st
Ground-truth points	2023	LULC validation	Field survey using Garmin GPS 64st
Landsat 5 Thematic Mapper (TM) (Collection 2, Level-2 SR)	14 June 2009	Baseline LULC mapping	USGS EarthExplorer
Landsat 9 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) (Collection 2, Level-2 SR)	15 June 2024	Recent LULC mapping	USGS EarthExplorer
Soil erosion	-	Estimate annual soil loss in the watershed	Adopted from Koirala et al. (2019) (https://doi.org/10.3390/geosciences9040147)
Topography	-	Derive watershed and lake boundaries, slope, and elevation.	Digital Elevation Model (DEM) from SRTM 30 m

Bathymetric survey

The bathymetric survey of Kupinde Lake was conducted using a hydroacoustic depth sounder (HDR 650 Humminbird®), coupled with Garmin GPS 64st, for precise spatial referencing (Neupane et al., 2022). The depth sounder has a maximum measurable depth of 180 m and was calibrated before data collection to account for offsets and instrument drift. GPS coordinates were recorded with an accuracy of ± 3 m. Over 500 depth measurements were collected across the lake along transects designed to systematically cover both shallow and deep zones, ensuring maximum spatial coverage of the watershed (Figure 1c).

In addition to depth measurements, morphological characteristics of the lakeshore were recorded, including slope gradients, inlet and outlet locations, surrounding land use, and notable geomorphic features. These observations were essential for understanding sediment deposition patterns and hydrodynamic influences on lake morphology.

LULC change

LULC of the Kupinde Lake watershed was analysed using Landsat TM (2009) and OLI (2024) satellite imagery. Images were pre-processed for atmospheric correction and geometric alignment. A supervised classification was performed using the Maximum Likelihood Classifier algorithm, which categorised the imagery into four key land use classes: agricultural land, forest land, barren land, and water bodies (Quincey et al., 2007; Rimal et al., 2017; Shrestha et al, 2022). Settlement areas were not classified as a separate category because of their small spatial extent and spectral similarity with agricultural land at both Landsat resolutions. Settlements were merged within the agricultural land category to maintain classification accuracy (Rimal et al., 2017; Shrestha et al., 2022).

Accuracy assessment was conducted using the ground-truth points collected from field surveys and high-resolution Google Earth imagery. Ground truthing for LULC classification was conducted in January 2023, and the resulting data were used to prepare the 2024 land use map. Following the common practice in LULC studies in Nepal, approximately 100 reference points per class were used to ensure reliable accuracy assessment (Rimal et al., 2017; Adhikari et al., 2022). The reference points were distributed across agricultural land, forest land, barren land and water bodies, and classification accuracy was evaluated through a confusion matrix (Rwanga & Ndambuki, 2017).

Soil erosion assessment

Soil erosion within the watershed was estimated using the Revised Universal Soil Loss Equation (RUSLE) model, data adopted from Koirala et al. (2019). The RUSLE model calculates average annual soil loss based on rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practices (P) factors. This approach allowed estimation of spatial patterns of soil loss and identification of high-risk erosion zones contributing to sedimentation in the lake. To calculate the total soil loss of the Kupinde watershed, the lake surface area was excluded from the total watershed area. The RUSLE outputs obtained from Koirala et al. (2019) were used to derive soil erosion rates (t ha^{-1} yr^{-1}) across the watershed. From these results, the average annual soil loss rate was computed for the watershed, while the maximum erosion rate was obtained directly as the highest pixel value within the watershed. The total annual soil loss (t yr^{-1}) was then calculated by multiplying the average soil loss rate by the effective watershed area (9.5 km^2). Finally, to convert mass into sediment volume, a bulk density of 1.45 t m^{-3} was applied (Koirala et al., 2019).

Bathymetric and morphometric analysis

Depth data were used to generate a bathymetric map and lake terrain elevation model using GIS and spatial interpolation techniques (Thakuri et al., 2021). From these models, key morphometric parameters such as lake surface area, volume, maximum depth, mean depth, and depth-volume-area relation were computed empirically, providing quantitative insights into lake storage capacity and sedimentation potential. Additionally, aerial photographs were acquired to support morphometric analysis (Figure 3a and 3b).

Figure 3. Lake bathymetry and aerial survey on January 14, 2023 (Drone Images: S. Thakuri)

RESULTS

Lake morphology

The bathymetric analysis of Kupinde Lake showed a total water volume of 6.14 million m^3, with an average depth of 24 m and a maximum depth of 37 m. The lake surface area at the waterline was approximately 259,568 m^2 (~ 0.25 km^2). Depth measurements indicated that the northern part of the watershed contained the deepest zones, while the southern margins were relatively shallow (Figure 4). The lake exhibits a marked reduction in both area and volume with depth, indicating a funnel-shaped (conical) basin geometry. More than two-thirds of the total storage lies within the upper 20 m, emphasising that the majority of the lake's water volume is concentrated in the shallower zones.

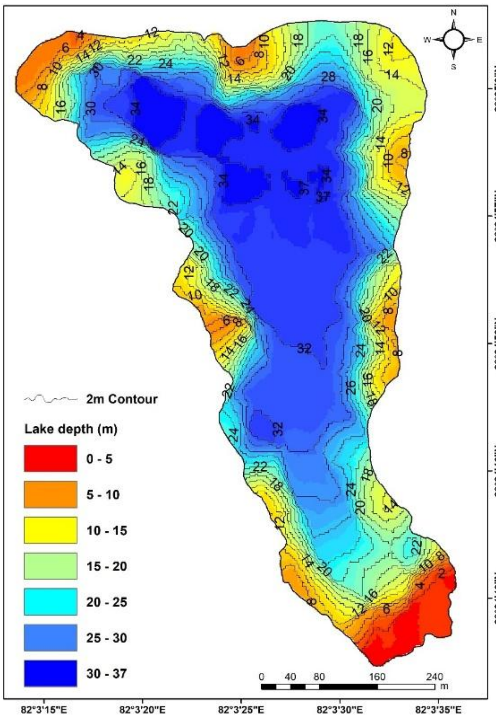

Figure 4. Bathymetry of Kupinde lake

At 5 m depth, the lake contained 4,915 thousand m³ of water and covered an area of 249,849 m^2, showing only a slight reduction from the surface values. By 15 m depth, the storage had decreased substantially to 2,674 thousand m^3, with the corresponding surface area reduced to 207,387 m^2, indicating a marked narrowing of the watershed. At 25 m depth, the lake volume declined further to 980 thousand m^3, accompanied by a surface area of 141,508 m^2, representing a considerable loss of storage capacity compared to the upper zones. Near the bottom at 35 m depth, the watershed held only 9 thousand m^3 of water, with a limited area of 21,048 m^2, reflecting the sharp contraction of both surface extent and volume at greater depths. These results highlight that the majority of lake storage is concentrated in the upper 20 m, while the lower watershed retains minimal water volume (Figure 5).

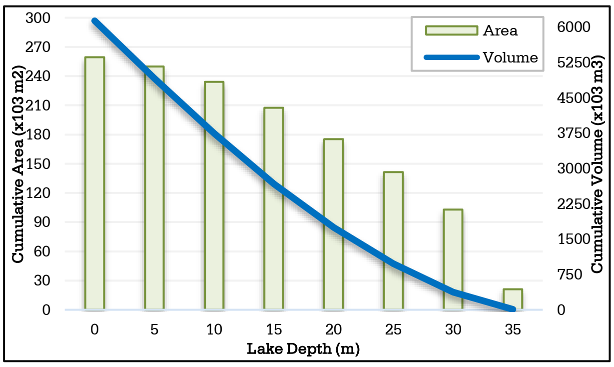

Figure 5. Depth–area–volume relationship of Kupinde Lake derived from bathymetric analysis

LULC change within the lake watershed

The supervised classification achieved an overall accuracy of 86% with a Kappa coefficient of 0.82, indicating a high level of reliability in the classification results. Between 2009 and 2024, the watershed experienced a decline in forest cover from 6.13 km² to 5.75 km² (6.2%) and a notable 60.5% increase in barren land (Figure 6 and Table 2). Agricultural land expanded slightly by 1.2%, while the area of water bodies increased by 17.4% (Table 2). The most significant land-cover changes were the reduction in forest area and the expansion of barren land within the watershed (Figure 6).

Table 2: LULC changes in the Kupinde Lake watershed between 2009 and 2024

Class	Area_2009(km²)	Area_2024(km²)	Change
Agricultural land	2.89	2.92	+1.2%
Baren land	0.50	0.81	+60.5%
Forest land	6.13	5.75	-6.2%
Water body	0.22	0.25	+17.4%

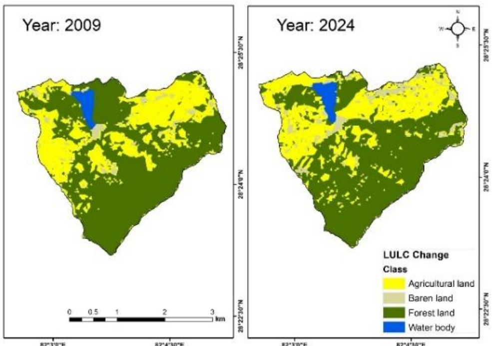

Figure 6. LULC change of the Kupinde Lake watershed

Lake erosion

The soil erosion analysis of the watershed revealed substantial variation in erosion intensity. The maximum estimated soil loss within the watershed was 182 t ha^{-1} yr^{-1}, while the average soil loss was 39 t ha^{-1} yr^{-1}. The total annual soil loss from the watershed was calculated at 36,821 t yr^{-1} (equivalent to 25,394 m^3 yr^{-1}). The majority of highly erodible areas are concentrated in the upper region (northern part) of the watershed, whereas the lower region exhibits comparatively less erosion (Figure 7).

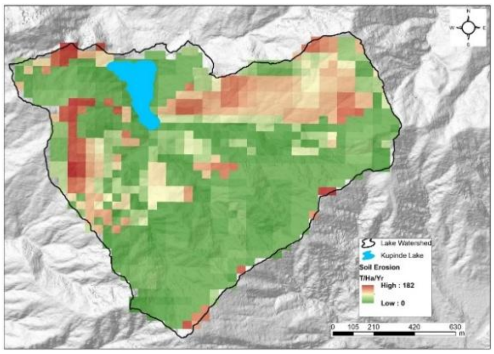

Figure 7. Soil erosion in the watershed of Kupinde Lake (map overlaid on hill shade background)

Lake sedimentation

With a total storage volume of about 6.14 million m^3, Kupinde Lake receives a measurable annual sediment input that may contribute to gradual lake infilling. Spatial evidence from aerial imagery, including highlighted zones in Figure 8, shows visible sediment deposition along the southern margin, indicating that inflowing streams serve as key pathways for sediment delivery. Given the conical-shaped watershed morphology, deposition is likely concentrated in littoral and inflow-proximal zones, while finer sediments may be transported towards the central watershed.

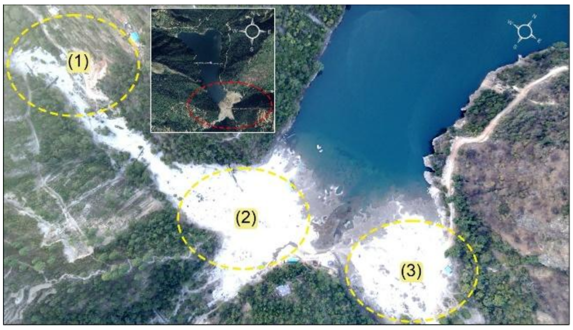

Figure 8. Sediment deposition in the Kupinde Lake, showing the erosion zone (1) and deposition zones (2 and 3). Photograph taken in January 2023.

DISCUSSION

Lake morphology and stratification

The bathymetric analysis of Kupinde Lake revealed a funnel-shaped watershed geometry with a maximum depth of 37 m and a surface area of approximately 259,568 m^2 (Figure 4). Similar geometry-based watersheds have been documented in other mid-hill and Himalayan lakes of Nepal, such as the Ramaroshan wetland complex in the far-western region and Gosaikunda Lake in the high Himalayas, where morphometric characteristics play a decisive role in controlling water retention and sediment distribution (Chalaune et al., 2020; Dhital, 2015; Neupane et al., 2022). The concentration of water volume in the upper 20 m suggests that the majority of aquatic habitats and nutrient cycling occur in these shallower zones, which are more accessible to light and support macrophyte growth (Dar et al., 2014; O'Brien et al., 2014).

Thermal stratification within the lake likely influences sediment deposition and biogeochemical cycling (Dean, 1999). During warmer months, the upper layer, or epilimnion, becomes well-mixed and oxygenated, while the denser, cooler hypolimnion remains isolated at greater depths (Cole, 1998). This stratification leads to distinct chemical and biological conditions between the layers, often resulting in variations in nutrient distribution and aquatic life diversity. Such dynamics not only inform researchers about ecological health but also highlight the lake's responsiveness to climatic changes, underscoring the need for ongoing monitoring to facilitate effective management strategies (Jeppesen et al., 2014).

Land use and land cover

The high classification accuracy (86%) strengthens confidence in the detected land-cover transitions, particularly the decline in forest cover and expansion of barren land. Such reliable LULC information provides a robust basis for linking landscape changes with the observed patterns of soil erosion and sediment influx into Kupinde Lake (Rimal et al., 2017; Rwanga & Ndambuki, 2017).

Changes in LULC within the Kupinde watershed have substantial implications for soil erosion and sediment dynamics. The observed increase in lake area during the LULC analysis may not solely represent hydrological expansion but can also be attributed to sediment deposition along the shorelines. Progressive deposition at the margins alters the lake boundary, where these infilled zones are often classified together with the water body in satellite imagery (Ovakoglou et al. 2016; Sabatier et al. 2022). Some evidence of such shoreline deposition can also be observed in Figure 8, supporting the interpretation that the apparent increase in lake coverage likely reflects both water spread and inclusion of depositional zones in the mapped extent.

The reduction in forest cover and expansion of barren land reflect patterns observed in other mid-hill regions of Nepal, where deforestation, overgrazing and land degradation increase soil susceptibility to detachment and transport (Guidi et al., 2015; Karki & Ojha, 2021; Nepal et al., 2018). Loss of vegetative cover diminishes root reinforcement and surface roughness, accelerating runoff and sediment mobilisation, particularly during intense monsoon rainfall events (Morgan, 2009; Puigdefábregas, 2005). Similar studies in the Himalayan watersheds highlight that exposed and degraded slopes serve as primary sources of sediment to downstream lakes and rivers, creating localised erosion hotspots (Ganie et al., 2024; Nepal et al., 2014).

Even minor anthropogenic modifications, such as the modest expansion of agricultural land and water bodies, can exacerbate soil disturbance, especially on marginal slopes or near inflows, contributing to enhanced sediment delivery (Stanley et al., 2012; Wassie, 2020). Comparison of the LULC and erosion maps for the Kupinde watershed shows that agricultural and forest land occupy the largest share of the catchment, and these land uses also account for most of the estimated soil erosion. Although forests are generally considered protective against erosion, steep slopes, deforestation and degraded patches contribute to notable sediment yield even from forested areas. Similar findings have been reported in some mid-hill watersheds of Nepal, where agriculture on sloping terrain and disturbed forest land were identified as dominant sources of soil loss (Paudel & Andersen, 2010; Rimal et al., 2017; Ghimire et al., 2013).

These LULC dynamics collectively indicate a shift towards more erosion-prone landscapes, emphasising the watershed's sensitivity to land-cover changes. Such insights reinforce the need for integrated watershed management approaches: reforestation, afforestation and soil conservation measures to mitigate erosion, sustain lake water quality and preserve ecosystem services within Kupinde Lake and similar Himalayan lakes (Mir et al., 2025; Roy et al., 2022; Zafirah et al., 2017).

Soil erosion in the watershed

Soil erosion within the Kupinde watershed exhibited substantial spatial variability, reflecting the heterogeneous nature of topography, land cover and anthropogenic activity. When scaled to the total watershed area of 9.75 km^2 (975 ha), the annual soil loss amounted to a volumetric loss of about 25,394 m^3 yr^{-1}. Such a magnitude of sediment availability underscores the watershed's potential to contribute significantly to sediment inflow and deposition within Kupinde Lake. These findings are consistent with studies conducted in other steep Himalayan watersheds, where soil erosion is highly sensitive to slope gradients, rainfall intensity and vegetation cover (Collins et al., 2011; Nepal et al., 2014; Tessema et al., 2024). In particular, the higher erosion rates observed in specific zones of the Kupinde watershed coincide not only with barren land and deforested slopes but also with intensively cultivated agricultural land, where soil disturbance and slope positioning amplify erosion risks. In contrast, forested areas exhibited the lowest erosion rates, underscoring the protective role of vegetation cover in stabilising slopes and reducing sediment mobilisation. This alignment between the LULC and erosion maps (Figures 6 and 7) highlights how both agricultural expansion and deforestation act as critical drivers of sediment input into Kupinde Lake, while forests function as natural buffers against erosion. Similar patterns were reported by Koirala (2010) and Uddin et al. (2018) in mid-hill watersheds of western Nepal, where deforestation and expansion of exposed soil surfaces led to localized erosion hotspots.

The spatial heterogeneity of soil loss within the Kupinde watershed also reflects the combined influence of natural and anthropogenic factors. Steep slopes amplify surface runoff during monsoon events, facilitating the detachment and transport of soil particles, while areas with reduced vegetative cover lack sufficient root structure to stabilise the soil. Additionally, land-use practices, including agriculture on marginal slopes, exacerbate erosion and increase sediment yield to the lake. Such processes are consistent with findings from Morgan (2009) and Chalise & Kumar (2020), who emphasised that small-scale land-use modifications in steep terrain can have disproportionately large effects on watershed-scale sediment flux.

The pattern of soil loss observed in the Kupinde watershed corresponds well with sediment deposition patterns in Kupinde Lake, particularly along the southern margin, where inflowing streams deliver eroded material (Figure 8). This spatial correspondence between erosion hotspots and deposition zones underscores the crucial role of watershed management in regulating sedimentation dynamics and preserving the quality of lake water. Over time, continued soil loss from highly erodible zones may accelerate lake infilling, reduce water storage capacity and alter aquatic habitats, with potential implications for biodiversity, nutrient cycling and local livelihoods.

Sedimentation dynamics

Sediment delivery into Kupinde Lake appears to be strongly controlled by watershed morphology, inflow characteristics and LULC changes. Aerial imagery and in-situ observations (Figure 8) reveal that deposition is concentrated along the southern margins and in zones proximal to inflowing streams, while finer sediments are transported towards the central watershed. This spatial variability is consistent with sedimentation dynamics reported for other Himalayan lakes, where inflow-dominated zones accumulate coarser material and distal areas receive finer sediments over time (Dhital, 2015; Dill et al., 2001). Human-induced erosion from deforested and barren lands likely amplifies sediment flux, contributing to gradual catchment infilling (Owens, 2020).

The interplay between conical geometry watersheds and episodic inflows results in heterogeneous sediment distribution, as reflected in the depth–volume relationships (Figure 5). Sediment deposition modifies the bathymetry, potentially reducing water depth in littoral zones and altering hydrodynamic circulation, which may affect oxygen distribution and habitat availability for aquatic species (Gibson et al., 2002; Ouillon, 2018; Thakuri et al. 2021). In addition, sediment accumulation influences water quality by increasing turbidity, altering nutrient dynamics and potentially accelerating eutrophication processes (Coffey et al., 2022). Over long timescales, these processes can transform Kupinde Lake from a deep, stratified watershed to a shallower system with expanded littoral areas, a phenomenon observed in other Himalayan lakes under similar sedimentation pressures (Bhuju et al., 2012; Shukla et al., 2002).

Implications for ecosystem and local communities

The combined effects of sedimentation and changing lake morphology have notable ecological and socioeconomic implications. Shallowing of littoral zones can enhance nutrient loading, promoting algal growth and potentially triggering eutrophication events (Devlin & Brodie, 2023; Paerl, 2006). Habitat alteration may reduce fish diversity and abundance, affecting local fisheries that many communities depend on for food and income (Lamsal et al., 2019; Wagle et al., 2007). Additionally, accelerated sediment deposition can reduce storage capacity, influencing water availability during dry periods (Einsele & Hinderer, 1997; Sabatier et al., 2022). These findings highlight the need for integrated watershed management strategies, including reforestation, soil conservation and sediment control measures, to sustain the ecological integrity of Kupinde Lake and support the livelihoods of surrounding communities.

CONCLUSION

Kupinde Lake has a surface area of about 0.25 km^2, a maximum depth of 37 m, a mean depth of 24 m and a storage capacity of approximately 6.14 million m^3. The bathymetric survey showed a funnel-shaped basin with most of the water volume concentrated in the upper 20 m, making the shallow and littoral zones particularly important for hydrological and ecological processes. The LULC analysis indicated a decline in forest cover and expansion of barren land, with agricultural areas also contributing to increased erosion. The watershed generates an estimated 36,821 t yr^{-1} of soil loss (equivalent to 25,394 m^3 yr^{-1} volume), part of which is visibly deposited along the lake's margins, contributing to localized sediment accumulation and progressive changes in lake morphology. These results confirm that sediment input from the surrounding watershed is directly influencing bathymetric change and lake area expansion. The study provides baseline information on lake morphometry, erosion and sedimentation, which can support ongoing monitoring and management. A limitation of this work is the reliance on a single bathymetric survey, modelled soil erosion data and short-term satellite observations, which may not fully capture seasonal or inter-annual variability. Therefore, long-term monitoring is recommended to better assess future lake dynamics and ecological responses.

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DATA AVAILABILITY STATEMENT

The datasets generated and analysed during the current study are available from the corresponding author on request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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