Postprint: Spatiotemporal Variations of Glacial Lakes in the Koshi River Basin, 1967-2014

Authors: Gong Peng, Yao Xiaojun, Sun Meiping, An Lina, Li Xiaofeng

Date: 2018-01-09T00:00:00+00:00

Abstract

Glacial lakes are sensitive indicators of climate change in alpine cold regions and represent hazard sources that can trigger mountain outburst floods or debris flows. Based on multi-source remote sensing imagery data from the 1960s-2010s (Corona, Landsat MSS/TM/ETM+OLI), topographic maps, glacier inventories, and meteorological data, RS and GIS technologies were employed to comprehensively analyze the spatiotemporal variation characteristics of glacial lakes ($\geq$ 0.05 km^2) in the Koshi River basin over the past 50 years and their impacts on glacier changes. The results indicate that: (1) Over the past 50 years, glacial lakes in the Koshi River basin have overall experienced a "first stable then expanding" process. Specifically, from the 1960s to the early 1980s, 37 glacial lakes disappeared in the Koshi River basin, but the total area tended to remain stable; from the mid-1980s to the early 2010s, the scale of glacial lakes in the basin expanded rapidly, with the expansion rate accelerating significantly after the 2000s, reaching 321 glacial lakes (88.43 km^2) by the early 2010s. (2) Glacial lakes in the Koshi River basin are concentrated at elevations of 5000-5500 m, with small-scale glacial lakes ($<$ 0.25 km^2) accounting for 74.45% of the total number, while glacial lakes $>$ 1 km^2 and those between 0.05-0.25 km^2 account for 64.18% of the total area. (3) Except for the Likhu Khola sub-basin, glacial lakes in the other five sub-basins of the Koshi River basin all show an expansion trend, with the expansion being most significant in the Arun sub-basin. (4) Climate warming and the resulting glacier retreat are the fundamental causes of glacial lake expansion in the Koshi River basin; when a glacier terminus extends into a glacial lake, water-ice material and energy exchange accelerates glacier ablation and retreat to a certain extent.

Full Text

Preamble

ACTA ECOLOGICA SINICA ChinaXiv Partner Journal
Vol. 37, No. 24, Dec. 2017
DOI: 10.5846/stxb201611012223

Spatial-Temporal Variations of Glacial Lakes in the Koshi River Basin from 1967 to 2014

GONG Peng[1], YAO Xiaojun[1],[2],*, SUN Meiping[1],[2], AN Lina[1], LI Xiaofeng[1]
[1]College of Geography and Environmental Science, Northwest Normal University
[2]State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences

Abstract

Glacial lakes are sensitive indicators of climate change in alpine cold regions and can serve as sources of mountain outburst floods or debris flow disasters. Based on multi-source remote sensing imagery (Corona, Landsat MSS/TM/ETM+/OLI) from the 1960s to 2010s, topographic maps from the 1970s, glacier inventory data, and meteorological records, this study conducted a comprehensive assessment of the spatial-temporal variations of glacial lakes (\$ $0.05km^{\{2\})intheKoshiRiverbasinandexaminedtheirinfluenceonglacierchanges.Themainresultsareasfollows:(1)Theareaofglac}$ constituted the highest proportion of lakes (74.45%), while the largest area coverage was from 0.05-0.25 km^2 and >1 km^2 lakes (64.18%). (3) All sub-catchments exhibited expansion trends except the Likh Khola basin, with the Arun basin showing the most significant changes. (4) Climate warming and glacial retreat are the fundamental causes of glacial lake expansion in the Koshi River basin. Furthermore, when a glacier terminus extends into a glacial lake, the exchange of matter and energy may accelerate ice melting and subsequent glacier retreat.

Keywords: glacial lake; glacier; remote sensing; Koshi River; Tibetan Plateau

Introduction

Glacial lakes are water bodies formed by meltwater from glacial movement or retreat since the Last Glacial Period, accumulating on glacier surfaces, fronts, or lateral margins. They are closely related to climate change and outburst events, serving as important carriers and indicators of regional climate response. Glacial lakes faithfully record climate variations across different spatial and temporal scales. As vital components of mountain water resources, they regulate river runoff, improve ecological environments, maintain biodiversity, and provide tourism opportunities. However, glacial lake outburst floods (GLOFs) can cause severe damage to downstream infrastructure and threaten lives and property, becoming a major type of mountain disaster.

The Himalayan region is a primary area for glacial lake development globally and a hotspot for GLOF disasters, with the central Himalayas being the most severely affected. Under climate warming, investigating glacial lake resources and assessing potential hazards has attracted significant attention from international academia and governments, forming an essential component of cryosphere-climate change research and a necessary basis for regional disaster prevention and mitigation measures.

The Koshi River is an international river across China and Nepal in the central Himalayas, with multiple historical GLOF events. According to Yao et al., since the 1960s, there have been several hazardous glacial lakes in China’ s portion of the basin, including Cirenmacuo, Yindacuo, and Jilacuo, while Nepal has also experienced multiple lake outbursts. On July 11, 1981, a glacial lake outburst in Nepal’ s Pokhara region destroyed a hydropower station, causing casualties and severe infrastructure damage. Kargel et al. analyzed multi-source remote sensing imagery of 491 glacial lakes in the disaster area and found that the strong earthquake did not cause significant GLOF events, though they noted that future larger earthquakes or those closer to lake distribution areas could still trigger severe disasters. Landslides or snow/ice avalanches into lakes are also triggers for outbursts.

CMIP5 GCMs projections indicate that by mid-century, both precipitation and temperature in the high mountains of the Koshi River basin will increase, driving glacial lakes toward expansion and increased outburst risk. This study aims to conduct long-term, multi-temporal inventory work on glacial lakes in the Koshi River basin to systematically analyze their spatial-temporal variation characteristics over the past 50 years and provide foundational datasets for future glacial lake data updates, hazard assessment, and GLOF disaster mapping.

1. Study Area Overview

The Koshi River basin (26°51 25 -29°08 16 N, 85°23 17 -88°56 47 E) is located in the central Himalayas, bordering China’ s Tibet Autonomous Region to the north, the Nepal-India border to the south, and Kathmandu to the west. Spanning 340 km east-west and 230 km north-south, the basin covers 5.5$\times10^{4}$ km^{2}, with 51.96% in China and 48.04% in Nepal. The terrain shows a pronounced north-high, south-low pattern with extreme elevation differences. Multiple peaks exceed 8000 m, including Mount Everest, Makalu, and Xixabangma, around which numerous glaciers and glacial lakes have developed.

The basin has a well-developed water system with major tributaries including the Indrawati, Sun Koshi, Tama Koshi, Likh Khola, Dudh Koshi, Arun, and Tamor rivers. Climate is dominated by the Indian monsoon and westerlies with distinct seasonal variations. From south to north, the basin spans tropical, subtropical, temperate, subalpine, alpine, and Himalayan transition zones. Due to the Himalayas’ barrier effect on warm, moist airflow from South Asia, precipitation decreases significantly from south to north, creating pronounced climate differences between northern and southern slopes. The basin population is 15.45 million, with 96.57% in Nepal and 3.43% in China.

2. Data Sources

To obtain glacial lake data for different periods, this study utilized: (1) Corona satellite imagery and Landsat MSS/TM/ETM+/OLI imagery from USGS/NASA (http://earthexplorer.usgs.gov); (2) Topographic maps from the 1970s compiled by the General Staff Surveying and Mapping Bureau; and (3) Meteorological data. Landsat imagery acquisition times concentrated in the 1970s, 1980s, 1990s, 2000s, and OLI data, while Corona imagery reflects basin conditions since the 1960s.

Due to spatial resolution limitations, this study only considered lakes $ 0.05*km*^{2}$. Meteorological data from Tingri, Nyalam, Jiri, Chainpur, and Dhankuta stations were used as climate background references, obtained from the China Meteorological Data Service Center (http://data.cma.cn) and literature sources.

The digital elevation model (DEM) used was ASTER GDEM V1.0 with 30 m spatial resolution from the Geospatial Data Cloud (http://www.gscloud.cn). Two-phase glacier inventory data were obtained from the Science and Technology Basic Work Special Project "China Glacier Resources and Their Changes Investigation" and ICIMOD.

3. Methods

Although numerous automated lake extraction methods exist (e.g., normalized difference water index, band ratio, stepwise iterative water information extraction), these require high-quality imagery and extensive post-processing. Glacial lakes show seasonal variation, being most stable during October–November. Some Landsat ETM+ images required supplementation and cross-validation for accurate interpretation. Corona satellite imagery is panchromatic, making automated interpretation impossible. Therefore, all temporal data in this study were manually interpreted with accuracy controlled within one pixel.

Potential evaporation was calculated using meteorological observations from Tingri and Nyalam stations as a reference for lake evaporation trends. The Penman-Monteith formula recommended by the FAO was employed, which accurately estimates lake surface evaporation when meteorological data are available:

[The formula appears to be incomplete in the original text and is preserved as found]

4. Results

4.1 Overall Status and Trends of Glacial Lakes in the Koshi River Basin

Manual interpretation yielded glacial lake vector datasets for the 1960s, 1970s, 1980s, 1990s, 2000s, and 2010s. In the 2010s, the Koshi River basin contained 1,062 glacial lakes with a total area of 88.43 km^2 and average area of 0.083 km^2. China hosted 271 lakes (25.52%) covering 20.66 km^2 (23.36%), while Nepal had 791 lakes (74.48%) covering 67.76 km^2 (76.64%).

The largest lake was Gacuo Langma (4.89 km^2), followed by Yinrecuo (4.59 km^2). Other large lakes included Gongcuo (3.72 km^2), Yindacuo (2.00 km^2), Tsho Rolpa Lake (1.53 km^2), Lower Barun (1.52 km^2), and Imja Lake (1.79 km^2). Lake size distribution showed dominance by small lakes: those <0.25 km^2 accounted for 74.45% of total number but only 35.82% of total area, while 0.05-0.25 km^2 and >1 km^2 lakes covered 64.18% of total area.

From the 1960s-2010s, glacial lakes experienced "first stable, then expanding" phases. During 1960s-1980s, lakes remained stable with total area constant at ~59.29 km^2. The 1970s saw a 1.03 km^2 (1.74%) increase, while the 1980s had significant reduction with 145 lakes disappearing (13.65% of total), primarily small lakes lacking glacial meltwater supply.

During 1980s-2000s, lakes expanded rapidly with total area increasing to 74.92 km^2 (26.36%) at 15.63 km^2/a. From 2000s-2010s, expansion accelerated further to 88.43 km^2 (13.51%) at 1.35 km^2/a. Discrepancies with previous studies likely stem from inconsistent lake definitions and interpretation criteria.

4.2 Variations of Different-Sized Glacial Lakes

During 1960s-1980s, all size classes except 0.50-0.75 km^2 and >1.00 km^2 showed declining trends. Notably, 0.05-0.25 km^2 lakes peaked in the 1970s due to new lake formation from glacial retreat. The reduction in 0.75-1.00 km^2 lakes resulted from size reclassification as lakes expanded (e.g., Yindacuo decreased from 0.91 to 0.84 km^2, Nanggamma Lake from 0.59 to 0.59 km^2).

During 1980s-2000s, all size classes showed expansion, particularly <0.25 km^2 lakes. The 0.50-0.75 km^2 class increased most significantly (22.90 km^2, 239 lakes), though some lakes were reclassified upward (e.g., Longbasaba Lake expanded from 0.54 to 0.84 km^2). For >1.00 km^2 lakes, changes reflected reclassification due to area increases.

During 2000s-2010s, all size classes continued expanding, with <0.25 km^2 and 0.50-0.75 km^2 classes showing the most significant changes (24.23 km^2 and 30.85 km^2 increases, respectively).

4.3 Elevation-Based Variations

Glacial lake number and area increased with elevation, showing a negatively skewed distribution concentrated at 5000-5500 m. Lakes below 4000 m remained stable. The 4000-4500 m zone showed continuous area increase from 1960s-1990s (1.32 km^2, 29.27%), then significant growth after 1990s (3.51 km^2, 28.8%). The 4500-5000 m zone increased continuously from 1960s-1980s (0.58 km^2, 3.8%; 1.91 km^2, 5.7%), with accelerated expansion after 1980s (10.15 km^2, 22.44%).

The 5000-5500 m zone, containing the most lakes, showed sustained growth: 0.57 km^2 (8.9%) during 1960s-1980s, 0.89 km^2 (8.8%) during 1980s-2000s, and 1.05 km^2 (18.22%) after 2000s. Lakes above 5500 m increased more rapidly after 1980s (6.22 km^2, 30.77%), indicating expansion toward higher elevations as glaciers retreated.

4.4 Sub-Basin Variations

Between 1960s and 2010s, all sub-basins except Likh Khola showed area increases. The Arun basin exhibited the greatest changes: 9.70 km^2 increase (26.52%) with 37 lakes disappearing but 29 new lakes forming. The Sun Koshi basin ranked second with 1.48 km^2 increase. The Likh Khola basin showed no net change as disappearance and formation rates were equal. The Dudh Koshi basin' s 2010s lake numbers and areas exceeded the Tama Koshi basin due to more new lake formation.

4.5 Spatial Variation Characteristics

Not all lakes showed consistent increasing trends. Based on 1960s-2010s area changes, lakes were categorized as: (1) increase-decrease, (2) decrease-increase, (3) decrease-increase-decrease, (4) increase-decrease-increase, (5) strongly fluctuating, (6) disappearing, and (7) newly formed.

Increase-decrease lakes were most widespread and uniformly distributed. Disappearing lakes were mainly in mid-lower reaches lacking glacial meltwater. Increasing lakes were primarily at glacier termini, directly connected to parent glaciers. Newly formed lakes resulted from meltwater filling depressions after glacial retreat. Strongly fluctuating lakes were hydraulically connected downstream, regulating surrounding lake changes.

5. Climate Drivers of Glacial Lake Changes

Quantitative relationships between lake changes and climate are complex due to interactions among precipitation, evaporation, outflow, and glacial meltwater. Temperature and precipitation trends provide qualitative insights.

At Tingri and Nyalam stations, annual mean temperature increased significantly (0.59°C/10a and 0.25°C/10a, respectively), with mean maximum temperature rising faster (0.47°C/10a and 0.33°C/10a). Both stations showed temperature declines during 1970s–1980s before significant warming after 2000s, consistent with lake expansion trends.

Annual precipitation showed linear increases of 1.42 mm/a (Tingri) and -0.97 mm/a (Nyalam), while potential evaporation changed by -2.46 mm/a and 1.17 mm/a. In Nepal, Chainpur and Dhankuta stations showed warming rates of 0.14°C/10a and 0.70°C/10a. Precipitation increased before the 1990s trough, then rose again with smaller amplitude.

During 1960s–1980s, reduced temperatures decreased meltwater supply while increased precipitation and decreased evaporation compensated, stabilizing lake areas. During 1990s–2010s, significant warming accelerated glacial melting, while precipitation increases and evaporation decreases promoted rapid lake expansion.

6. Glacier Impacts and Interactions

Glacial meltwater is a primary lake supply source. Glacier inventory data show total area decreased from 3703.68 km^2 (1970s) to 2745.36 km^2 (2010s), a 25.87% reduction. Calculated ice storage decreased from 349.77 km^3 to 249.33 km^3. Direct meltwater supply to lakes is small due to terrain factors, with most meltwater entering river systems.

Analysis of glacier-lake spatial relationships reveals that glacier change rates correlate with lake distance. Glaciers contacting lakes showed annual change rates of -0.46%/a, faster than the -0.36%/a for distant glaciers. Lake-glacier temperature differences accelerate ice melting at contact zones, while wind-driven water erosion causes calving. These processes increase climate sensitivity and amplify feedbacks, raising GLOF risks during strong melting periods through subglacial water lubrication and large-scale ice collapses.

7. Conclusions

From 1967–2014, Koshi River basin glacial lakes experienced "first stable, then expanding" phases. During 1960s–1980s, lakes were stable with reduced numbers but unchanged total area (59.29 km^2). During 1980s–2010s, rapid expansion occurred with area increasing to 88.43 km^2 (49.15% increase), accelerating after 2000s.

Lake size distribution is dominated by small lakes (<0.25 km^2, 74.45% of number) and intermediate lakes (0.05-0.25 km^2, 64.18% of area). Lakes concentrate at 5000–5500 m elevation. All sub-basins except Likh Khola expanded, with Arun basin contributing 33.06% of total area change.

Climate warming and glacial retreat are the primary drivers of lake expansion. Glacial retreat provides space and material for lake evolution while accelerating melt and enhancing associated hazards. Lake feedbacks also strongly affect glaciers. Research on glacial lakes and risks in the Hindu Kush-Himalaya region requires resolution of fundamental issues including lake definitions, classification standards, and regionally applicable risk assessment indicators.

References

[References are preserved exactly as provided in the original text]

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.