# Development of glacial lakes in the Everest and Kangchenjunga regions, Nepal Himalaya

A

Thesis

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# Abstract

The widespread loss of glacier mass in the Himalaya is the evidence of the recent climate change. Increased melt rates of the glaciers and changes in their morphology are leading to the formation and expansion of glacial lakes. These features are usually formed on gently sloping debris-covered glaciers. They are at different stages of development in remote and poorly inhabited regions. Such lakes are dammed by fragile materials and may break and cause glacial lake outburst floods (GLOFs). This study examined the evolution and dynamics of glacial lakes at seasonal to decadal timescales using assessments of remotely sensed satellite imageries and field measurements.

Inventories of glaciers and glacial lakes were prepared for the Everest region, upper Dudh Koshi River basin using WorldView and GeoEye imageries of 2015 and 2016 of 2-m spatial resolution. The inventory revealed a total of 109 glaciers with a total surface area of 268.22 ± 1.46 $km^2$. The largest number of glaciers (n=27) was recorded in the Khumbu Glacier basin, while the largest area of glaciers (86.22 ± 0.33 $km^2$) was found in the Ngozompa Glacier basin. The number of debris-covered glaciers was 25 with the surface area of 239.99 ± 1.07 $km^2$. Similarly, a high-resolution inventory of the glacial lakes discovered a total of 3,290 glacial lakes with a total surface area of 8.11 ± 0.45 $km^2$. The supraglacial lakes were found most frequently among all types of glacial lakes, and they accounted for 91% of the total number of glacial lakes. The inventory also suggested that the largest area of supraglacial lakes appeared on the surface of large debris-covered glaciers with gently sloping surface and larger mean width. The inventory of the glacial lakes for the Kangchenjunga region using Sentinel-2 imagery of 10-m spatial resolution revealed a total of 373 glacial lakes with a total surface area of 6.18 ± 0.75 $km^2$ in 2018, where unconnected glacial lakes (n=221) were most frequent.

The Landsat imagery interpretation for the long-term development of supraglacial lakes in the Everest region revealed the continuous increase in the area and the number of the lakes from 1989 – 2017, with minor fluctuations. Similarly, seasonal dynamics of supraglacial lakes using Sentinel-2 showed the smallest lake area during the winter season, while the area of these features was comparable during the pre-monsoon and post-monsoon seasons. Measurements of the supraglacial lakes from 1989 – 2017 revealed the highest persistence of the lakes at the terminus of the eight glaciers, i.e., Thyanbo, Chhule, Melung, Bhote Koshi, Lumsamba, Ngozompa, Khumbu, and Nuptse glaciers, which are

termed as spillway lakes. These spillway lakes are expanding at faster rates and Ngozompa, Bhote Koshi, Khumbu, and Lumsamba glaciers suggested that a trajectory towards large lake development. Both the analyse of DEMs, generated from the UAV survey in 2018 and freely available DEM of the year 2010 for the spillway lakes on the Ngozompa Glacier suggested the larger surface lowering rate in the lake area than the downstream of the lake area, which is suitable condition for becoming a single large glacial lake on the glacier.

Analyses of CORONA, Landsat and Sentinel-2 images revealed the net increase in the surface area of glacial lakes by 230% in the Kangchenjunga region from 1964 to 2018. The increase in the lake area was largely contributed by glacier-fed lakes (68%), while the increase in the number of unconnected and non-glacier-fed lakes indicated the retreat of the glaciers in the study region. New proglacial lakes in the Kangchenjunga region were found expanding at faster rates after 2000, while proglacial lakes that were developed in the earlier period (1960 – 1980) were mostly at static state. Similarly, traces of five GLOFs were for the first time discovered based on the geomorphological evidence detected by CORONA and Landsat image analyses: they had occurred before the 1980s in the Kangchenjunga region.

This study demonstrated the efficiency of the use of different spatial resolution imageries to map the different sized lakes. It also revealed that WorldView imagery of 2-m resolution can be used to map the feature of size >500 $m^2$ with uncertainty <15% semi-automatically. This can be suitable for accuracy assessment of the results from moderate and coarse resolution imageries. In addition, 2-m spatial resolution images can be used to map features as small as the size of 20 $m^2$ by applying manual corrections. Similarly, Sentinel-2 of 10-m and Landsat of 30-m spatial resolution determine the surface of the lakes that have size >0.02 $km^2$ and >0.1 $km^2$, respectively, under an uncertainty threshold of 15%.

The study of the glacial lakes in the Everest and Kangchenjunga regions presented the rapid increase in their number and area, which is caused by increasing melt rates due to the warming trend of temperatures. Besides, the identification of five GLOF events for the first time improved the knowledge of past GLOFs in the Kangchenjunga region. Formation of new lakes and rapid expansion of already developed lakes may increase the possibility of occurrence of GLOFs. Therefore, continuous monitoring of the glacial lakes is required to understand their physical setting, hazard parameters, and associated risk, which can help to minimize the risk for the people living in the downstream region.