# 学 位 論 文 審 査 の 要 旨

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Development of glacial lakes in the Everest and Kangchenjunga regions, Nepal Himalaya
（ネパール・ヒマラヤ，エベレストおよびカンチェンジュンガ地域における氷河湖の発達）

The widespread loss of glacier mass in the Himalaya is evidently caused by the recent climate change. Increased melt rates of glaciers and changes in their morphology are leading to the formation and expansion of glacial lakes. Glacial lakes are usually formed on gently sloping debris-covered glaciers in remote and poorly inhabited regions, and are at different stages of development. Such lakes are dammed by fragile materials and may 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$^2$. Comparison among the basins showed that the largest number of glaciers (n=27) was observed 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 total 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 to 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 to 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 the four of the Ngozompa, Bhote Koshi, Khumbu, and Lumsamba glaciers suggested that a trajectory towards large lake development. Analyses both of DEM, generated from the UAV survey in 2018 and of freely available DEM of 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 evolving into a single large glacial lake on the glacier. On the other hand, the rest of the four supraglacial lakes (Thyanbo, Chhule, Melung, and Nuptse) did not show the clear trajectory because of their slower rates of expansion, which is possibly controlled by the geometry of the glaciers.

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 in a stable state. Similarly, geomorphological analysis by CORONA and Landsat images succeeded, for the first time in the Kangchenjunga region, to identify the traces of five GLOFs that had occurred before the 1980s. This identification filled the information gap and improved the knowledge on the past GLOFs.

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 imageries 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 with the size >0.02 $km^2$ and >0.1 $km^2$, respectively, under an uncertainty threshold of 15%.

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.

In addition to the excellent academic knowledge in the research, his academic records throughout the Ph.D. course are excellent. Based on these evidences, the committee reached to a conclusion that Mohan Bahadur Chand deserves to become a Doctor of Environmental Science.