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学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

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）

Widespread loss of glacier mass in the Himalaya is evidently caused by the recent climate change. Increased melt rates of the glaciers and changes in their morphology are leading to 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 the remote and poorly inhibited regions. Such lakes are dammed by fragile materials and may break and cause glacial lake outburst floods (GLOFs). This thesis examined 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 2-m resolution WorldView and GeoEye imageries of 2015 and 2016. The inventory revealed a total of 109 glaciers with a total surface area of 268.22 ± 1.46 km^2. The number of debris-covered glaciers, i.e., glaciers with debris cover at their ablation zone, was 25 with the surface area of 239.99 ± 1.07 km^2. Similarly, high-resolution inventory of glacial lakes discovered a total of 3,290 glacial lakes with a total surface area of 8.11 ± 0.45 km^2. Supraglacial lakes were found most frequently among all types of the glacial lakes, and they accounted for 91% of the total number of the 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 that

there existed 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 clarified the long-term development of supraglacial lakes in the Everest region and 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. Measurement of the supraglacial lakes revealed the presence of spillway lakes on eight glaciers. These spillway lakes are expanding at faster rates and Ngozompa, Bhote Koshi, Khumbu, and Lumsamba glaciers, suggesting a trajectory towards large lake development. Both the analyses of DEMs, generated from the UAV survey in 2018 and freely available DEM for the spillway lakes of the Ngozompa Glacier of the year 2010, suggested the higher 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%). 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 stable state. Similarly, traces of five GLOFs were for the first time discovered based on the geomorphological evidences detected by CORONA and Landsat image analyses: they had occurred before the 1980s in the Kangchenjunga region.

This study demonstrated the efficiency of 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 >0.0005 km^2 with uncertainty <15% semi-automatically. In addition, 2-m spatial resolution images can be used to map features as small as size of 20 m^2 by applying manual corrections.

This study presented the rapid increase in the number and area of glacial lakes, which could be attributed to increasing trend of temperatures. Further, identification of five GLOF events that have occurred in the Kangchenjunga region improved the knowledge on GLOFs. 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 regions.