जलवायु
JALAWAAYU
(Interdisciplinary Journal of Atmospheric and Hydrospheric Sciences)
Journal home page: https://cdhmtu.edu.np/journal/index.php/jalawaayu

Research Article

Glacier Area, Mass and Associated Glacial Lake Change in Kawari basin, Western Nepal

Nitesh Khadka[1,2,*], Nirab Shrestha[3], Kajol Basnet[3], Roshan Manandhar[4], Shankar Sharma[5], Bhaskar Shrestha[2,6], Krishna Prasad Sigdel[7]

1 Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China
2 University of Chinese Academy of Sciences, Beijing, China
3 The Small Earth Nepal, Kathmandu
4 Pulchowk Campus, Institute of Engineering, Tribhuvan University
5 Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu
6 State Key Laboratory of Remote Sensing Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China
7 Central Department of Botany, Tribhuvan University, Kathmandu

ARTICLE INFO

Received: 1 October 2022
Received in Revised form: 9 November 2022
Accepted: 22 December 2022
Available Online: 12 February 2023

Keywords
Glacier
Mass balance
Glacial lake
Remote sensing
Nepal

**Correspondence*
Nitesh Khadka
E-mail: niteshkhadka48@gmail.com

Abstract: Due to ongoing global climate change, the glaciers in the Himalaya are shrinking and the glacial lakes are increasing in number and area. This study investigates the glacier area change, mass balance and associated glacial lake evolution in the headwaters of Kawari basin, western Nepal using optical remote sensing images. The results indicate that eleven glaciers in the study area have shrunk by 1.64 km^2 between 1994 and 2021. In the same period, due to glacier recession glacial lake formed and expanded by 0.0103 km^2 yr^{-1} reaching 0.34±0.042 km^2 in 2021. Surface elevation change of glaciers revealed that the ablation zone of glacier thinned up to -8.18 m between 2000 and 2019. The specific mass balance of eleven glaciers was calculated to be -0.3 m w. e. yr^{-1} from 2000 to 2019. The study of glaciers is important as they are visible signals of climate change, and their changes often impact water resources and mountain hydrology.

Cite this paper: Khadka, N., Shrestha, N. ., Basnet, K., Manandhar, R., Sharma, S., & Shrestha, B. Glacier Area, Mass and Associated Glacial Lake Change in Kawari basin, Western Nepal. *Jalawaayu*, *3*(1), 63–72. https://doi.org/10.3126/jalawaayu.v3i1.52068

1. Introduction

The climate of the world is continuously changing, and such changes are reflected in variations of glacier extent and mass (Bolch et al., 2012). The status of the glaciers is different in different regions of the world; some glaciers in certain region may be advancing and while others may be retreating (Yao et al., 2012). For example, glaciers in the Karakoram have gained positive mass balance or in the state of balance while glaciers in the Himalayas are reported to be losing mass at an accelerated rate (Bolch et al., 2017; Brun et al., 2017). A climate change influences a glacier most directly by changing the net inflow or outflow of mass determined by snowfall, melt, and related processes, i.e., mass balance. Melt on warm summer days and intense rainfall increase the volume of water reaching the glacier bed, a process that often changes the ice flow (Cuffey and Paterson 2010). The mass balance of Himalayan glaciers was same with global average until 2000 but likely negative after 2000 (Azam et al., 2018). The mass wastage in the Himalaya has resulted in increasing debris cover, the growth of glacial lakes and possibly decreasing ice velocities (Azam et al., 2018; King et al., 2018; Thakuri et al., 2014).

One of the consequences of climate change induced glacier loss is the formation and expansion of glacial lakes in the alpine environment (Zhang et al., 2015). Glacial lakes in the Himalaya are continuously evolving in number, surface area and volume (Nie et al., 2017). Such changes in glacial lakes increase the risk of glacial lake outburst floods (GLOFs) events. GLOF occur when the water retain in glacial lake release due to several triggering factors like avalanche, earthquake, dam failure by hydrostatic pressure or melt of buried ice (Khadka et al., 2021). GLOF have the strongest capacity to destruct low lying areas including settlements, infrastructure, agriculture land and killing people. Further, it is reported that the future deglaciation will likely increase the cases of GLOF events in the Himalaya and surroundings (Zheng et al., 2021).

Across Nepal Himalaya, the glaciers are continuously shrinking, retreating and being fragmented since 1970s due to ongoing climate change (Bajracharya et al., 2014). It is reported that glacier have shrunk by ~24 % between ~1980s and 2010 (Bajracharya et al., 2014) and simultaneously surface area of glacial lake have expanded by ~25% between 1987 and 2017 over Nepal (Khadka et al., 2018). Moreover, some glacial lakes are expanding rapidly in Nepal (Khadka et al., 2022). Mostly, field and remote sensing-based glacier and glacial lake studies are confined to eastern Nepal, especially in Everest region. For instance, Meera and Pokalde glaciers have been studied by glaciological method (Wagnon et al., 2013) and several studies have measured the bathymetry of Imja Tsho in the Everest region (Lala et al., 2018; Somos-Valenzuela et al., 2014; Watanabe et al., 1994) and studied Tsho Rolpa in the Rolwaling area (Shrestha and Nakagawa 2014; Sakai et al., 2000). Moreover, Sugiyama et al., (2013) outlined that Yala glacier in Langtang region lost ~40% of ice volume between 1982 and 2009 with accelerating thinning at rates in recent decades (-0.69±0.25 vs –0.75±0.24 m a^{-1} during 1982–96 and 1996–2009). Field measurement for a year shows -0.088±0.019 m w. e. mass balance of Rikha Shamba glacier in Dhulagiri region from September 2011 to October 2012 (Gurung et al., 2018). The glaciers in the Everest region had a thinning rates of -0.40 m yr^{-1} between 2003 and 2009 based on ICEsat data (Gardner et al., 2013) and with an average annual rate of mass loss of -0.26 ± 0.13 m w.e. yr^{-1} between 2000 and 2011

(Gardelle et al., 2013). In contrast, there are few or no studies of glacier shrinkage and glaciological mass balance in the western part of Nepal due to remote location and difficulty in accessibility. Thus, this study selects the Mt. Saipal region in Western Nepal to observe the changes in glaciers and associated glacial lake as this region is previously not studied and manual visualization in Google Earth have showed the rapid evolution of glacial lake in recent years in the study region. Specifically, the main objective of the paper is to calculate and analyze: (1) the glacier area changes between 1994 and 2021, (2) surface elevation changes and mass balance between 2000 and 2019, and (3) associated changes in the glacial lake area in the headwater of Kawari basin.

2. Materials and Methods

2.1. Study Area

Geographically, the study area is located in the Far-western part of Nepal in the Bajhang district, which is extended from 81.52° to 81.9° East longitudes and 29.85° to 29.92° North latitudes. The study area lies in the headwater of Kawari sub-basin of Karnali river basin covering an area of ~72 km^2 (Figure 1). The highest peak in the region is Mt. Saipal (7,031 m). The study area is profoundly affected by westerlies in the winter season and by south Asian monsoon in summer season (Sharma et al., 2020a; Sharma et al., 2020b). There are eleven glaciers in the study area and the highest elevation of glacier is ~6800 m and the lowest elevation is ~3600 m (Bajracharya et al., 2014).

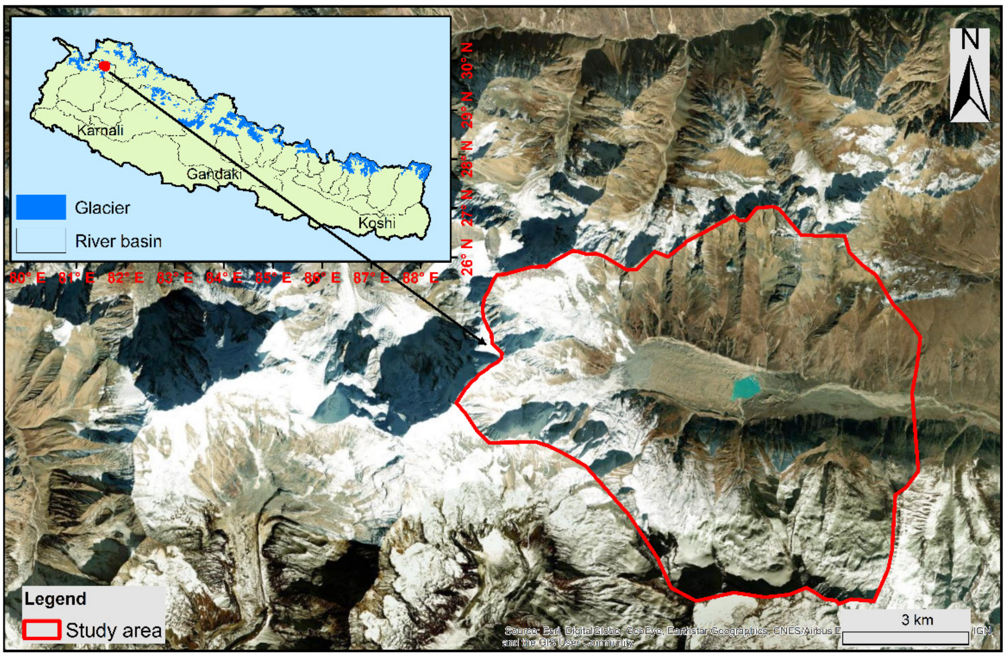

Figure 1. *Location of study area in Nepal*

2.2. Data used and method

We used geometrically corrected Landsat 5/7/8 images of 1994, 2004 and 2021, respectively, of post-monsoon season with minimum seasonal snow cover and cloud cover. These images were downloaded from the United States Geological Survey's (USGS) web portal (www.earthexplorer.usgs.gov). Landsat data are widely used to map glaciers and glacial lakes because of their high temporal coverage, spatial-resolution (30 m) and open access (Roy et al., 2014). The other data used were the Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM, 30 m) data which were downloaded from the National Aeronautics and Space Administration's (NASA)web portal (https://urs.earthdata.nasa.gov). SRTM-DEM was used to delineate study area and hydrology of glaciers.

The glacier outlines were semi-automatically delineated from Landsat images of 1994 and 2021 using normalized difference snow index (NDSI) selecting optimal threshold to distinguish glacier cover over other surfaces. NDSI is defined as the ratio of difference between green and short-wave infrared (SWIR) bands and their sum. Manual post-correction was applied by visually checking and editing for shadow components and improving the glacier delineation using false color composite images by single expert. The debris cover part of the glacier was delineated using Google Earth and with the help of previous glacier inventories (Bajracharya et al., 2014). The error in glacier area extent was obtained as the product of one pixel and perimeter of glacier polygon, i.e., the average area of one pixel buffer inside and outside of the glacier polygon (Khadka et al., 2020; Racoviteanu et al., 2015).

Similarly, glacial lake was delineated using normalized difference water index [($\varrho G - \varrho NIR$)/($\varrho G + \varrho NIR$)] with manual correction from false color composite images (Khadka et al., 2018). The error in glacial lake area was calculated as the as a product of the half the resolution of data used and the lake's perimeter (Salerno et al., 2012).

For the mass balance calculation of the glaciers, the DEM difference data was obtained from Thiea Cartographic layer which was generated and corrected from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-DEM from 2000 to 2019 (http://maps.theia-land.fr/theia-cartographic-layers.html?year=2022&month=07&collection=glaciers). xDEM— an open-source python package was used to carry out surface elevation change per elevation bins, glacier volume and change calculation (Dehecq et al., 2022). The DEM difference data (surface elevation change), glacier outline and reference DEM were the inputs. Since, the elevation change has been already obtained, the calculation of the mean elevation change per glacier bin was calculated using glacier outline. The 25 m elevation bin was prepared from the minimum to the maximum elevation of glacier. Following the calculation of the mean elevation change over the glacier per elevation, the volume change was carried out by summing up the mean elevation change and product with the bins area. The change in mass was obtained by multiplying the change in volume with the mass conversion factor of 850 kg/m^3. Finally, the specific mass balance was calculated in meter water equivalent (m.w.e) by diving the change in mass with the average area between the two glacier outlines.

3. Results and discussions

3.1. Glacier mapping and area change

The glacier mapping reveals 11 glaciers in the study area covering an area of 14.04±2.17 km^2 in 2021. The glaciers size ranges from 0.075 to 7.75 km^2 with mean size of 1.28 km^2. Of these, one glacier is debris covered and largest among them with area of 7.75±0.97 km^2. These glaciers had total area of 15.68±2.22 km^2 in 1994 based on Landsat 5 image. Total area of these glaciers decreased by 1.64 km^2 (-10.45 %) in 27 years between 1994 and 2021 (Figure 2). Figure 2 reveals that glaciers have subsequently decreased in area especially in the terminus position and consequently glacier lake is being formed. The largest glacier with debris covered in the ablation zone decreased by -7.97 % (-0.67 km^2) while remaining clean glaciers decreased by -8.66% from 1994 to 2021. The expansion of debris covered part was insignificant in the study area as the debris covered part was insignificantly increasing while the terminus was retreating due to lake expansion at the same time.

The results of glacier area change in the study area (-0.35% yr^{-1}) is comparable with glacier area change (-0.5% yr^{-1}) in the eastern region of Nepal (Ojha et al., 2016). The changes in glaciers are often attributed to ongoing climate change and local topographical factors. The shrinkage and retreat of glaciers are due to observed increase in temperature and decrease in precipitation (Thakuri et al., 2014). It has been reported that the maximum air temperature has been increasing at high altitudes of Nepal from mid 1970s (Shrestha et al., 1999). Similarly, the precipitation have been reported to be decreasing in far western provinces and higher altitude of Nepal (Sharma et al., 2021; Sharma et al., 2020b). A study of hydro-climatic variability in Karnali river basin of western Nepal illustrated that the maximum temperature trend during the pre-monsoon season is significantly higher (0.08^{o}C yr^{-1}) followed by winter season during 1981 to 2012 (Khatiwada et al., 2016).

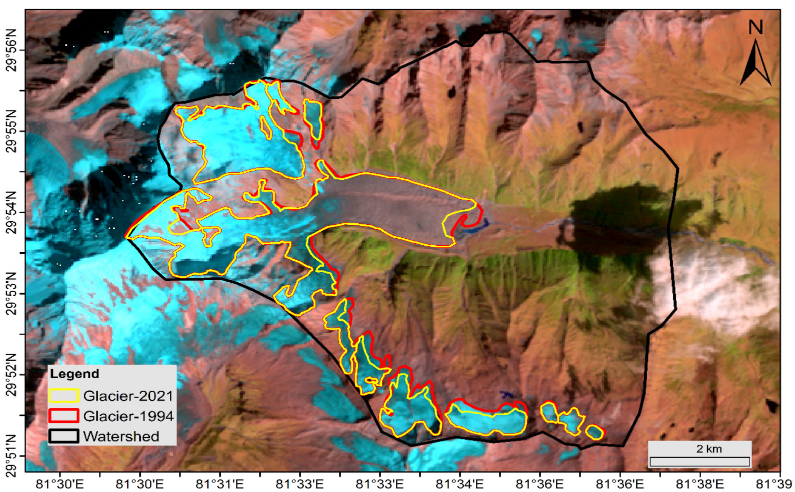

Figure 2. Changes in glaciers between 1994 and 2021. The background is false color composite Landsat image of 1994.

3.2 Glacier surface elevation change and mass balance

Figure 3a shows the surface elevation change of glaciers in the range between +3.01 and -5.56 m from 2000 to 2019. The results shows that the negative change (thinning) is pronounced at the ablation zone and foot of the glaciers while positive change is observed in the accumulation zones of glaciers at higher elevations. The hypsometry of glaciers reveal that glaciers are concentrated between 4500m to 5500m (Figure 3b). Small glaciers and glaciers terminus at lower elevation are thinning rapidly compared to the accumulation zone over 6000 m is quite positive or static.

The simulated results show that the total volume change of glaciers is -53,40,124.20 m^3 from 2000 to 2019. Similarly, the total mass change of glaciers is -4539105.57 t for 19 years. The computed results revealed that the specific mass balance of eleven glaciers was found to be -0.3 m w. e. yr^{-1}.

Snowfall is the major source for glaciers. It has been observed that the snow cover area has been decreasing in western Nepal (Khadka et al., 2020) which has resulted in the thinning of the glaciers. The result of specific mass balance of this study corroborates with other regional studies of Nepal. For example, it was reported that the glaciers of Everest region exhibited mass loss of -0.26 ± 0.13 m w.e. yr^{-1} between 2000 and 2011 (Gardelle et al., 2013) and similarly, the specific mass loss of -0.32 ± 0.08 m w.e. yr^{-1} for 1970–2007 was reported by Bolch et al., (2011) which is inline with our finding. The reason for glacier changes in the lower elevation compared to higher elevation can be inferred by two reasons. Firstly, the impact of elevation dependent warming is insignificant to drive glacier thinning at higher elevations (Li et al., 2020) and temperature is below freezing point at higher elevations. Secondly, the average snow line altitude (SLA) of glaciers in the western Nepal lies between 4500-5000 m (Khadka et al., 2020), which means the equilibrium line of altitude of glaciers is higher than SLA indicating that higher elevations receive significant snowfall.

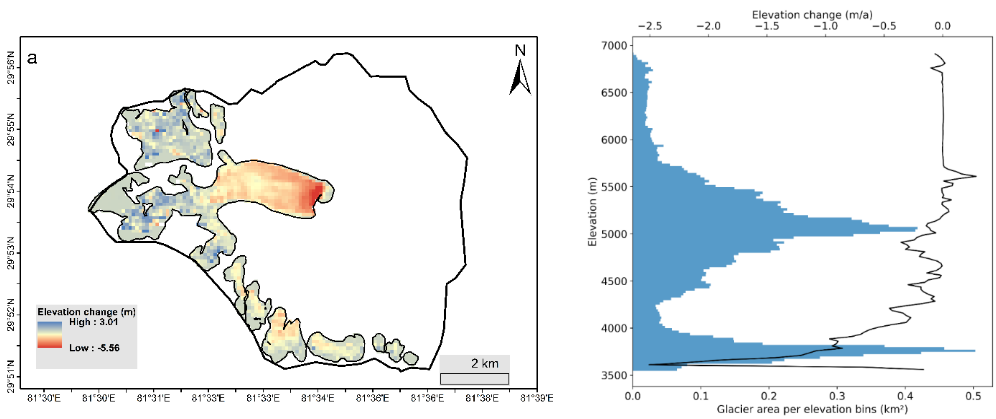

Figure 3. *Surface elevation changes of glaciers between 2000 and 2019*

3.3 Glacial lake evolution

The shrinkage and thinning of glaciers (as shown in Sections 3.1 and 3.2) have resulted in the formation and subsequent expansion of glacial lake between 1994 and 2021 in the terminus position of debris covered glacier (Figure 4). The mapping shows that the initial area of glacial lake was 0.061±0.026 km^2 in 1994 which evolved to 0.25±0.04 km^2 in 1994 reaching to 0.34±0.042 km^2 in 2021 (Table 1). Over 27 years, glacial lake grew by 0.279 km^2 (~457%) and the annual change of glacial lake is calculated to be 0.0103 km^2 yr^{-1}.

The growth of glacial lake area will ultimately increase the potential flood volume of glacial lake. Additionally, the rapid increase in glacial lake area will turn the lake into potentially dangerous in future and increase the risk of GLOF event from it (Khadka et al., 2019). The lake has possibility of future expansion when demonstrated from modelled glacier thickness (Farinotti et al., 2019) and slope derived from DEM. Moreover, the rate of calving and glacier-lake interaction determines the future expansion of glacial lake (Khadka et al., 2021). Nepal is one of the countries highly affected by GLOF events with higher socio-economic consequences (Carrivick and Tweed 2016). Glacial lake not only pose threat to downstream but are also drivers of glacier recession. Lacustrine terminating glaciers are retreating at faster rates, causing the proglacial lakes to expand, meanwhile, the thermal cutting from the lake water is enhancing the calving and retreating of glaciers (King et al., 2019).

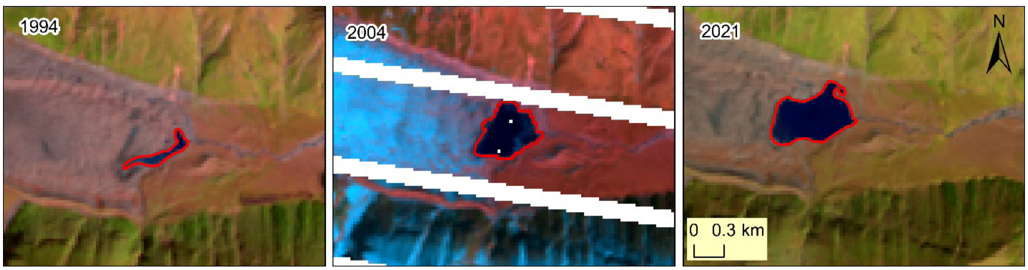

Figure 4. *Evolution of glacial lake from 1994 to 2021. The stripes in 2004 is due to scan line failure in Landsat 7.*

Table 1. *Changes in glacial lake area*

Year	Area (km^2)
1994	0.061±0.026
2004	0.25±0.04
2021	0.34±0.042
Total change (2021-1994)	0.279 km^2 in 27 years

4. Conclusions

In this study, we observed the changes in glaciers and associated glacial lake in the head waters of Kawari basin in the Mt. Saipal regions of western Nepal using remote sensing datasets. The results show that eleven glaciers in the study area are shrinking from 15.68±2.22 km^2 in 1994 to 14.04±2.17 km^2 in 2021. The calculated specific mass balance of these glaciers is -0.3 m w. e. yr^{-1} between 2000 and 2019. Additionally, the glacial lake is growing due to glacier recession. We conclude that the ongoing climate change has impacted the glaciers and glacial lakes in the study area. The retreat of glaciers will affect the water balance in downstream while expansion of glacial lake will pose threat to downstream communities in future.

Acknowledgments: This study is based on the project work of 2022 Winter School in Application of Field and Remote Sensing Techniques for Snow and Glacier Studies held in Kathmandu Center for Research and Education, Kirtipur, Kathmandu, Nepal. We would like to acknowledge KCRE, CAS-TU; IRD-FRANCE and CDHM, TU for the Winter School. The first author is supported by CAS-TWAS fellowship. We would also like to acknowledge the organization and individuals involved for providing open access data used in this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

Azam, M. F., P. Wagnon, E. Berthier, C. Vincent, K. Fujita and J. S. Kargel (2018). "Review of the status and mass changes of Himalayan-Karakoram glaciers." Journal of Glaciology **64**(243): 61-74.

Bajracharya, S. R., S. B. Maharjan, F. Shrestha, O. R. Bajracharya and S. Baidya (2014). Glacier status in Nepal and decadal change from 1980 to 2010 based on Landsat data, International Centre for Integrated Mountain Development.

Bolch, T., A. Kulkarni, A. Kääb, C. Huggel, F. Paul, J. Cogley, H. Frey, J. S. Kargel, K. Fujita and M. Scheel (2012). "The state and fate of Himalayan glaciers." Science **336**(6079): 310-314.

Bolch, T., T. Pieczonka and D. Benn (2011). "Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery." The Cryosphere **5**(2): 349-358.

Bolch, T., T. Pieczonka, K. Mukherjee and J. Shea (2017). "Brief communication: Glaciers in the Hunza catchment (Karakoram) have been nearly in balance since the 1970s." The Cryosphere **11**(1): 531.

Brun, F., E. Berthier, P. Wagnon, A. Kääb and D. Treichler (2017). "A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016." Nature geoscience **10**(9): 668-673.

Carrivick, J. L. and F. S. Tweed (2016). "A global assessment of the societal impacts of glacier outburst floods." Global and Planetary Change **144**: 1-16.

Cuffey, K. and W. Paterson (2010). "The physics of glaciers, 4th edition." Elsevier: 704.

Dehecq, A., E. Mannerfelt, R. Hugonnet and A. Tedstone (2022). xDEM-A python library for reproducible DEM analysis and geodetic volume change calculations, Copernicus Meetings.

Farinotti, D., M. Huss, J. J. Fürst, J. Landmann, H. Machguth, F. Maussion and A. Pandit (2019). "A consensus estimate for the ice thickness distribution of all glaciers on Earth." Nature Geoscience **12**(3): 168-173.

Gardelle, J., E. Berthier, Y. Arnaud and A. Kaab (2013). "Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011 (vol 7, pg 1263, 2013)." The Cryosphere **7**(6): 1885-1886.

Gardner, A. S., G. Moholdt, J. G. Cogley, B. Wouters, A. A. Arendt, J. Wahr, E. Berthier, R. Hock, W. T. Pfeffer and G. Kaser (2013). "A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009." science **340**(6134): 852-857.

Gurung, S., B. C. Bhattarai, R. B. Kayastha, D. Stumm, S. P. Joshi and P. K. Mool (2018). "Study of annual mass balance (2011-2013) of Rikha Samba Glacier, Hidden Valley, Mustang, Nepal." Sciences in Cold and Arid Regions **8**(4): 311-318.

Khadka, N., X. Chen, N. Yong, S. Thakuri, G. Zheng and G. Zhang (2021). "Evaluation of Glacial Lake Outburst Flood susceptibility using multi-criteria assessment framework in Mahalangur Himalaya." Frontiers in Earth Science **8**: 748.

Khadka, N., S. K. Ghimire, X. Chen, S. Thakuri, K. Hamal, D. Shrestha and S. Sharma (2020). "Dynamics of maximum snow cover area and snow line altitude across Nepal (2003-2018) using improved MODIS data." Journal of Institute of Science and Technology **25**(2): 17-24.

Khadka, N., S. K. Ghimire, S. Sharma and K. Hamal (2022). "Rapidly Expanding Glacial Lakes in Nepal Himalaya." Jalawaayu **2**(1): 45-55.

Khadka, N., G. Zhang and W. Chen (2019). "The state of six dangerous gla-cial lakes in the Nepalese Himalaya." Terr. Atmos. Ocean. Sci **30**: 63-72.

Khadka, N., G. Zhang and S. Thakuri (2018). "Glacial lakes in the Nepal Himalaya: Inventory and decadal dynamics (1977–2017)." Remote Sensing **10**(12): 1913.

Khatiwada, K. R., J. Panthi, M. L. Shrestha and S. Nepal (2016). "Hydro-climatic variability in the Karnali River basin of Nepal Himalaya." Climate **4**(2): 17.

King, O., A. Bhattacharya, R. Bhambri and T. Bolch (2019). "Glacial lakes exacerbate Himalayan glacier mass loss." Scientific Reports **9**(1): 1-9.

King, O., A. Dehecq, D. Quincey and J. Carrivick (2018). "Contrasting geometric and dynamic evolution of lake and land-terminating glaciers in the central Himalaya." Global and Planetary Change.

Lala, J. M., D. R. Rounce and D. C. McKinney (2018). "Modeling the glacial lake outburst flood process chain in the Nepal Himalaya: reassessing Imja Tsho's hazard." Hydrology and Earth System Sciences **22**(7): 3721-3737.

Li, B., Y. Chen and X. Shi (2020). "Does elevation dependent warming exist in high mountain Asia?" Environmental Research Letters **15**(2): 024012.

Nie, Y., Y. Sheng, Q. Liu, L. Liu, S. Liu, Y. Zhang and C. Song (2017). "A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015." Remote Sensing of Environment **189**: 1-13.

Ojha, S., K. Fujita, K. Asahi, A. Sakai, D. Lamsal, T. Nuimura and H. Nagai (2016). "Glacier area shrinkage in eastern Nepal Himalaya since 1992 using high-resolution inventories from aerial photographs and ALOS satellite images." Journal of Glaciology **62**(233): 512-524.

Racoviteanu, A. E., Y. Arnaud, M. W. Williams and W. F. Manley (2015). "Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern Himalaya." The Cryosphere **9**(2): 505-523.

Roy, D. P., M. Wulder, T. R. Loveland, C. Woodcock, R. Allen, M. Anderson, D. Helder, J. Irons, D. Johnson and R. Kennedy (2014). "Landsat-8: Science and product vision for terrestrial global change research." Remote sensing of Environment **145**: 154-172.

Sakai, A., K. Chikita and T. Yamada (2000). "Expansion of a moraine-dammed glacial lake, Tsho Rolpa, in Rolwaling Himal, Nepal Himalaya." Limnology and oceanography **45**(6): 1401-1408.

Salerno, F., S. Thakuri, C. D'Agata, C. Smiraglia, E. C. Manfredi, G. Viviano and G. Tartari (2012). "Glacial lake distribution in the Mount Everest region: Uncertainty of measurement and conditions of formation." Global and Planetary Change **92**: 30-39.

Sharma, S., Y. Chen, X. Zhou, K. Yang, X. Li, X. Niu, X. Hu and N. Khadka (2020a). "Evaluation of GPM-Era Satellite Precipitation Products on the Southern Slopes of the Central Himalayas Against Rain Gauge Data." Remote Sensing **12**(11): 1836.

Sharma, S., N. Khadka, K. Hamal, B. Baniya, N. Luintel and B. B. Joshi (2020b). "Spatial and Temporal Analysis of Precipitation and Its Extremities in Seven Provinces of Nepal (2001-2016)." Applied Ecology and Environmental Sciences **8**(2): 64-73.

Sharma, S., N. Khadka, B. Nepal, S. K. Ghimire, N. Luintel and K. Hamal (2021). "Elevation dependency of precipitation over southern slope of central Himalaya." Jalawaayu **1**(1): 1-14.

Shrestha, A. B., C. P. Wake, P. A. Mayewski and J. E. Dibb (1999). "Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94." Journal of climate **12**(9): 2775-2786.

Shrestha, B. B. and H. Nakagawa (2014). "Assessment of potential outburst floods from the Tsho Rolpa glacial lake in Nepal." Natural hazards **71**(1): 913-936.

Somos-Valenzuela, M., D. C. McKinney, D. R. Rounce and A. Byers (2014). "Changes in Imja Tsho in the Mount Everest region of Nepal." The Cryosphere **8**(5): 1661-1671.

Sugiyama, S., K. Fukui, K. Fujita, K. Tone and S. Yamaguchi (2013). "Changes in ice thickness and flow velocity of Yala Glacier, Langtang Himal, Nepal, from 1982 to 2009." Annals of glaciology **54**(64): 157-162.

Thakuri, S., F. Salerno, C. Smiraglia, T. Bolch, C. D'Agata, G. Viviano and G. Tartari (2014). "Tracing glacier changes since the 1960s on the south slope of Mt. Everest (central Southern Himalaya) using optical satellite imagery." The Cryosphere **8**(4): 1297-1315.

Wagnon, P., C. Vincent, Y. Arnaud, E. Berthier, E. Vuillermoz, S. Gruber, M. Ménégoz, A. Gilbert, M. Dumont, J. M. Shea, D. Stumm and B. K. Pokhrel (2013). "Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007." The Cryosphere **7**(6): 1769-1786.

Watanabe, T., J. D. Ives and J. E. Hammond (1994). "Rapid growth of a glacial lake in Khumbu Himal, Himalaya: prospects for a catastrophic flood." Mountain Research and Development: 329-340.

Yao, T., L. Thompson, W. Yang, W. Yu, Y. Gao, X. Guo, X. Yang, K. Duan, H. Zhao and B. Xu (2012). "Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings." Nature climate change **2**(9): 663.

Zhang, G., T. Yao, H. Xie, W. Wang and W. Yang (2015). "An inventory of glacial lakes in the Third Pole region and their changes in response to global warming." Global and Planetary Change **131**: 148-157.

Zheng, G., S. K. Allen, A. Bao, J. A. Ballesteros-Cánovas, M. Huss, G. Zhang, J. Li, Y. Yuan, L. Jiang and T. Yu (2021). "Increasing risk of glacial lake outburst floods from future Third Pole deglaciation." Nature Climate Change **11**(5): 411-417.