North American Academic Research

Journal homepage: http://twasp.info/journal/home

Review Article

Glaciers, glacial lakes and glacial lake outburst floods in the Khumbu region, Nepal

Tina Rai[1,2,3*], Mukesh Rai[3,4]

[1]Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[2]Key Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[3]University of Chinese Academy of Sciences, Beijing 100049, China

[4]State Key Laboratory of Cryosphere Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Gansu 73000, China

[*]Corresponding author

E-mail: dimmalikrisha123@gmail.com

Telephone number: +8618801220301

Accepted:*31st May, 2020;* ***Online***: *01June, 2020*

***DOI** : https://doi.org/10.5281/zenodo.3872556*

Abstract: *Climate changes have a direct impact on glaciers that ultimately results in glacial retreat, creating a high risk from catastrophic glacial lake outburst floods (GLOFs). The GLOFs are glacier disaster, which is the result of sudden discharge of large volume of water with debris from proglacial or supraglacial lakes in valley downstream. The research on glaciers would give the light on the increasing effect of climate change as glaciers are the sensitive indicator of climate change and create the mitigations for the damages of it. Here, the information regarding the glaciers, glacial lakes and GLOFs in the Khumbu region were reviewed from previous studies. This gives a general overview of the Khumbu region and its glacial components.Khumbu region is one of the most glacierized regions with the 'Khumbu glacier', the largest glacier of Nepal. The retreating of glaciers in the Khumbu region is also evidenced by the increase in glacial lakes and leading to the potential danger GLOFs which result in destruction of downstream settlement. The mitigating measures needs to implement immediately to prevent future GLOFs prone destructions.*

Keywords: *glacial lakes, glacial lake outburst floods, glaciers, Khumbu region*

Introduction

Hindu Kush Himalayas (HKH), defined by its glaciers, covers various peaks from North to North-Eastern regions of the Indian subcontinent which spread among Bhutan, Nepal, India, China (Tibet) and Pakistan (Bajracharya et al., 2015; Venkatachalam & Prabagaran, 2015). Most of the Himalayas landscape falls on the geographical boundaries of Nepal and India with higher coverage (two-third) in Nepal. It spreads out approximately 2500 km in length, 250 km in width and an area of 590,000 km^2(Barnett et al., 2005; Richardson & Reynolds, 2000; Xu et al., 2009). Nearly 70% of the world's fresh water is frozen in glaciers, and the HKH have more than 54,000 glaciers with 2300 to 7200 km^3 glacier ice volumes besides the Polar Regions and considered as the dynamic storage of freshwater (Bajracharya et al., 2015; Dyurgerov & Meier, 2005; Frey et al., 2014). This region has been named as the 'Water Tower of Asia', as it provides around 8.6×10^6 m^3 of water annually (Bolch et al., 2012; Dyurgerov & Meier, 1997; Immerzeel et al., 2010). This meltwater help in the survival of more than 750 million people and support the economy of the countries by providing water for irrigation, hydropower, manufacturing and domestic usage (Immerzeel et al., 2010; Pritchard, 2017).

Nepal is a small landlocked and mountainous country covering an area of 147,181 km^2 extending from 26º22' to 30º27'N and from 80º04' to 88º12' E. It is surrounded by highly elevated valley and dry areas of the central Himalayas which are the most extreme but least prioritized environments on Earth (Rai, 2005; Venkatachalam & Prabagaran, 2015).Its elevation varies from 60 m a.s.l. in the south to 8848 m a.s.l. in the north within a horizontal distance of less than 200 km. Nepal is affected by two major weather systems, summer monsoon circulation (June to September) and westerly circulation from October to May (Immerzeel et al., 2012; Ueno et al., 2008; Whiteman, 2000). During the summer, the river discharge increases as a result of the southwest monsoon in river basins which ultimately cause floods and landslides (Salerno et al., 2015; Shrestha et al., 2000). The Himalayan Region consist 200 peaks of >6000 meters high and 13 peaks of more than 8000 meters high, including the world's highest peak Mount Everest (in Nepali "Sagarmatha") at 8848m, with the variation in topography, weather, and biodiversity within the small latitudinal difference. Physiographically, Nepal is divided into three parts: the high Himalayas with 24% of the country's total area in the north; the hills and mountains (56%) in the center and the plain Terai (20%) in the south .

The transboundary river system exists in Nepal with Tibet, China in the north and India in the east, west and south (Chen et al., 2013). The Koshi river basin, Gandaki river basin, Karnali river basin, and Mahakali river basin are the main river basins of Nepal which are located in Eastern, Central, Western and Far Western regions respectively. The Koshi river basin lies in eastern Nepal and neighboring areas of China from longitude 85.48 to 88.70 E and latitude 27.53 to 28.95 N. It has seven major sub-basins: the Tama Koshi, Arun, Dudh Koshi, Likhu, Tama, Sun Koshi, and Indrawati. Dudh Koshi is the most important sub-basins in terms of glaciers and glacial lakes (Bajracharya et al., 2007). The South Asian monsoon has a high influence on the glaciers of the Khumbu region which results in the maximum precipitation in summer, leading to high glacier sensitivity to temperature (Grove, 2004).

Materials and methods

This study is mainly focused on the information found online which was accessed through google scholar, science direct, and web of science peer reviewed journals. Literature was searched using the keywords (glaciers, glacial lakes, glacial lakes outburst floods, Dudh Koshi basin, Khumbu region) and further sorted the results based on the study area (Nepal) (Fig.1). The listed literature was studied and the information regarding our study was noted.

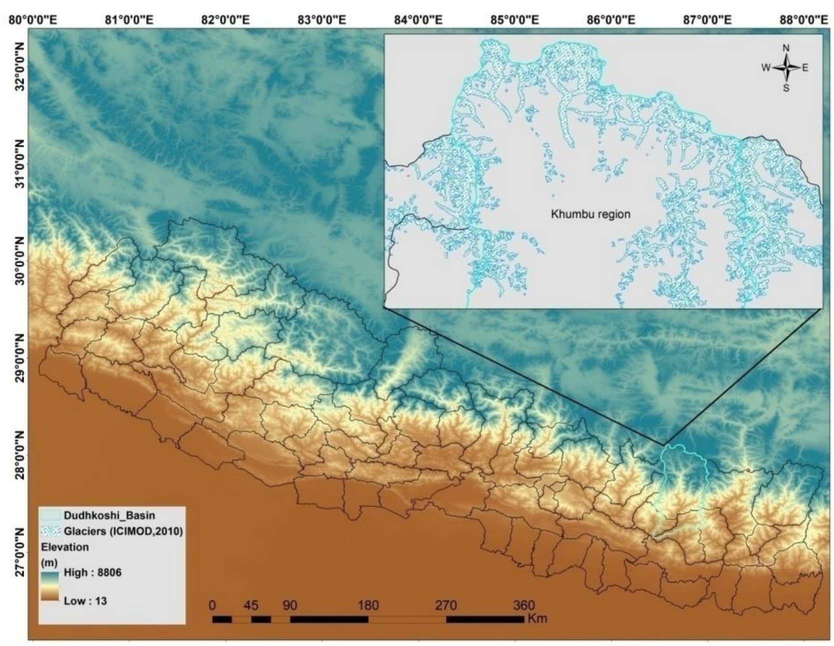

Fig. 1 Location of study area

Result and Discussion

Glaciers and glacier retreat

Glaciers occupy approximately 10% of the Earth's total land area and most are situated in the Polar Regions like Antarctica and Greenland with some located in mountainous regions above snowline (Lemke et al., 2007; Shakti et al., 2013). The glacier is divided into five ecological zones: supraglacial zone (snow and ice); englacial zone (ice); subglacial zone (sediments); proglacial zone (streams and lakes) and glacier forefields(Hotaling et al., 2017). The largest mountain glaciers are found in the central Himalayan region and HKH is the origin of the largest river basins in Asia and provide water to 1.3 billion people (Bolch et al., 2012; Immerzeel et al., 2010; Xu et al., 2009). The length of glaciers ranged from less than 1 km to 24 km in the Nepal Himalaya (Azam et al., 2018). The lowest part of the glacier is known as ablation zone while above snow line (in case of glaciers of Nepal, 4000m above mean sea level), it is an accumulation zone. The glacierized area in the Himalayas varies from 36,845 to 50,750 km^2(Azam et al., 2018) and Nepal Himalaya is regarded as the most glaciated part of Himalaya (Fujita & Nuimura, 2011; Salerno et al., 2012).

Glaciers are considered as the storage of freshwater for river systems which has important aspects such as generating hydroelectric power, sediment transportation, and formation of landforms including scientific fields i.e. sites (Jansson et al., 2003). They resemble the best indicator of climate change and significant impacts can be observed such as rapid glacier melting (Moore et al., 2009; Oerlemans, 2001). The glacier melting leads to the formation of new glacial lakes, the increase in the size of moraine-dammed lakes and cause the risk of GLOFs (glacial lake outburst floods) (Watanabe et al., 1994). On the basis of the 2001 inventory, there were 3252 glaciers in Nepal with a total area of 5324 km^2 (Mool et al., 2001)whereas the 2010 inventory identified 3808 glaciers with an area of 4212 km^2(Bajracharya et al., 2010; Bajracharya & Shrestha, 2011) and later reported with 3900 km^2(Bajracharya et al., 2014). Among 278 glaciers in the Dudh Koshi catchment as shown in Table 1, 40 largest glaciers exert 70% of the glacierized area with 482 km^2 (Bajracharya & Mool, 2009). These glaciers have an increase in the total area of glacier surfaces since the 1960s and surface-lowering rates over recent decades (Nuimura et al., 2012; Thakuri et al., 2014)

Table 1: Details of Dudh Koshi Basin (Bajracharya & Shrestha, 2011)

Parameters	Dudh Koshi basin
Basin area	4062 km^2
Latitude	27.64 – 28.10
Longitude	86.52-87
Number of glaciers	287
Clean glacier area	304.42 km^2
Debris Covered glacier area	110.68 km^2
Total glacier area	415.09 km^2
Elevation	4344-8222 m a.s.l.
Total ice reserves	41.62 km^3
Clean glacier elevation	4588-8222 m a.s.l.
Debris Covered glacier elevation	4344-5996 m a.s.l.

The majority of Himalayan glacier's retreat started in the mid 19^{th} century with different rates from glaciers to glaciers (Ageta, 1993; Bolch et al., 2012; Fujita & Nuimura, 2011; Fujita et al., 2009). Glacier retreating is a threat to the Nepal Himalayas as it would have an impact on the hydrological cycle to which the downstream population fully depends on for their living. All the glaciers have negative mass balance as shown in Table2; the proof of glacier is retreating. The remarkable changes have been observed in the Mt. Everest region: rapid and accelerating loss of ice from glaciers (Bolch et al., 2012). The number of glaciers found in the Dudh Koshi basin was 287 with an area of 415.09km^2 and an ice volume of 41.62 km^3(Bajracharya & Shrestha, 2011). Ngozumpa, Khumbu, Bhote Koshi, and Hungu glaciers are the principal glaciers in this basin. The longest glacier in this basin is Ngozumpa Glacier with an area of 81 km^2 and Imja Tsho is the largest lake with an area of 0.95 km^2, one of the fastest-growing lakes in the entire Himalaya (Bajracharya et al., 2007).

Table 2: General characteristics of glaciers of Khumbu region (Watson et al., 2017)

Glaciers	Lon	Lat	Area (km^2)	Length (km)	Min-max elevation (range)m	Gradient (º)	Period (1970-2007) Glacier Geodetic mass balance estimate (m.w.e.a^{-1})	Period (2000-2015) Glacier Geodetic mass balance estimate (m.w.e.a^{-1}) (King et al., 2017)
Ama Dablam	86.86	27.88	2.29	4.44	4769-5084(315)	1.6	-0.29±0.08	
Barun	87.02	27.88	53	9.17	5018-5453(435)	1.5	-	
Changri Nup	86.79	27.99	4.62	5.75	5057-5540(483)	1.6	-0.28±0.08	
Changri Shar			2.75	4.84	5074-5436(362)	1.6	-0.28±0.08	
Gaunara			4.33	7.70	4983-5432(449)	1.6	-	
Imja	86.94	27.9	1.18	2.56	5023-5187(164) 6431	1.6	-0.50±0.09	–0.79 ± 0.24
Kangshung			10	12.1	4586-5377(791)	1.6	-	
Khumbu	86.83	27.98	6.54	10.9	4856-5446(590) 6523	1.6	-0.27±0.08	–0.35 ± 0.15
Lhotse	86.92	27.92	5.76	6.73	4815-5245(430)	1.6	-0.26±0.08	–0.65 ± 0.14
Lhotse Nup			1.4	3.88	4954-5210(256)	1.6	-0.18±0.07	
Lhotse Shar			3.03	4.05	5008-5329(321)	1.6	-0.50±0.09	
Ngozumpa	86.71	28.02	83	15.8	4668-5241(573)	1.5	-	–0.53 ± 0.19
Nuptse	86.87	27.95	3.04	6.19	4962-5554(592)	1.6	-0.25±0.08	

Khumbu Glacier

Khumbu glacier, linked by the ridge connecting Everest, Lhotse, and Nuptse, is 17 km in length widely known as the trekking route to Everest Base Camp (Hambrey et al., 2008). It is the representative glacier with elevation ranging between 4900 to 8848 m with area 6.54 km^2, which is conducive to moraine-dammed lake formation in near future with key features as steep avalanche-prone flanks, icefall ponds, lower 6 km debris mantled.

Ngozumpa Glacier

One of Nepal's longest glaciers, Ngozumpa glacier (28°00'N and 86°45'E) is debris covered valley glacier with length 18 km and area 83km^2. It flows from south-southeast from the flanks of Cho Oyu (8188 m) and Gyachang Kang (7922 m) (Benn et al., 2001). The glacier is mantled by supraglacial debris to the lowermost 15 km with snow field altitude 6400 to 6800 m (Williams et al., 2010)

Chukhung Glacier

The 2.5km long Chukhung Glacier lies at the east of Ama Dablam and has own suite of moraines (Hambrey et al., 2008). The glacier is a steeply sloping crevassed remnant on the slope of a high ridge with lateral-terminal moraine complex. The moraine used to have a lake which was discharged through the outburst flood.

Lhotse Glacier

The Lhotse Glacier extends 8.5 km from the 3000m high headwall of Lhotse's south face to snout is located at the west of Imja Tsho. The upper 4 km consists of crevasses and fractured bedrock which indicate that part being active whereas the remainder is covered with lichen and moss-covered boulders, pointing stagnation and the moraine is not conducive to dam formation (Hambrey et al., 2008; Quincey et al., 2007).

Imja Glacier

Imja glacier is comprised of two major tributaries: Lhotse Shar Glacier, the larger northeastern component (4.5 km long) and Imja Glacier itself, the southeastern component, lies in eastern Khumbu Himal. Both of the tributaries ended in the moraine-dammed Imja Tsho. Both of the glaciers are fed by avalanches from Lhotse Shar (8383 m) and Baruntse (7168 m) with debris-mantled and supraglacial ponds (Hambrey et al., 2008).

Glacial lakes

When a glacier retreat leaving the debris at the end of the glacier then it forms a dam called moraine which traps the melting water from glacier and form a lake, glacial lake. The Himalaya's glacial lakes are connected to the glacier terminus and have small area as compared to glacial lakes of Tibet which are larger in area (Zhang et al., 2017; Zhang et al., 2015). Since

1960s, new glacial lakes have been emerging as the result of notable warming in Himalayas and still their number is increasing (Bolch et al., 2008; Shrestha et al., 1999; Zhang et al., 2015). In 2017, one study revealed 1541 glacial lakes with a total area of 80.95±15.25 km^2 in Nepal (Khadka et al., 2018) and this indicate the increment number of lakes than the previous study by (ICIMOD, 2011) which reported 1466 glacial lakes. The glacial lakes range from 2456 to 5908m with mean elevation of 4873m and almost 98% of the glacial lake lies above 4000m. The size of glacial lakes differs from small glacial lakes of 0.05km^2 to maximum 4.61 ± 0.33km^2.

Out of the 1541 glacial lakes, 1064 (64.69 km^2) were identified as glacier-fed lakes and 477 (16.26 km^2) as non glacier-fed lakes. Similarly, 1064 glacier-fed lakes were divided into 166 (2.33 km^2) supraglacial lakes and 349 (30.52 km^2) proglacial lakes and 549 (31.84 km^2) unconnected glacier-fed lakes (Khadka et al., 2018). Among four major river basins of Nepal, the Koshi river basin has the maximum glacial lakes as well as the mean elevation of these glacial lakes is the lowest as compared to other river basins. Supraglacial lakes are reported high in number in Everest region of the Koshi river basin, where debris cover was found to increase by ~18% between 1962 to 2011 (Thakuri et al., 2014; Watson et al., 2016). Among the sub basins of Koshi, Dudh Koshi catchment consist of 170 unconnected glacial lakes (4.28 km^2), 17 proglacial lakes (1.76 km^2) and 437 supraglacial lakes (1.39 km^2) (Salerno et al., 2012).

In total, 21 glacial lakes have been known as potentially dangerous glacial lakes (PDGL) and among these, 6 glacial lakes (Imja Tsho, Tsho Rolpa, Thulagi, Chamlang South, Lumding Tsho, and Lower Barun Tsho) are given more attention as they tends to extend faster than others as well as they are in high risk of bursting (ICIMOD, 2011). Previous studies on GLOFs showed the heavy destruction which cause the loss of life and property and effect on economic status with damage of hydropower work, roads, and other infrastructures (Lutz et al., 2016; Richardson & Reynolds, 2000). The different characteristic features of the glacial lakes have impact on its expansion rate. With the increasing in the area and deepening of glacial lakes, results in expansion of its volume and ultimately increase the chance of potential flood.

Imja Tsho

Most of the attention for the research has been done in Imja Tsho which is located at the lower part of the Imja-Lhotse Shar glacier and it flows through the moraine dam, forming Imja Khola which is a tributary of Dudh Koshi (Chen et al., 2013; ICIMOD, 2011) . It is located in the easternmost part of the Sagarmatha region in Solukhumbu district (27º53'55''N, 86º55'21''E; 5000 m a.s.l.), near to one of the world's highest massifs Everest-Lhotse which is dammed by ice-cored moraine to the west and lateral moraines to the north and south whereas calving front of Imja/Lhotse Shar glaciers to the east (Haritashya et al., 2018). The development of Imja Tsho started as a pond in the 1950s (Watanabe et al., 1994) and the area was found to be 0.028km^2 in 1962 (Bajracharya et al., 2007). The surface area expansion of Imja Tsho ranges from 0.19 km^2 in 1975 to 1.30 km^2 in 2017 with average growth of about 0.03 km^2 yr^{-1}(Haritashya et al., 2018)and the expansion of the lake could result in the increase of its hazard profile as it is susceptible of incoming avalanches. This will have devastating results as it is situated on the trek route of Everest and the villages built that support those activities as well as the calving ice fronts make them vulnerable for the dam failure. With the growing risk of GLOF seen in Imja lake, its level had been reduced by 3.4 m in 2016 (Cuellar & McKinney, 2017) that account 10% drainable volume.

Glacial lake outburst flood

Glacial lake outburst flood (chhu-gyumha, Sherpa word for it) caused due to the sudden release of the water from the moraine- or ice-dammed lakes which can be stored within topographic lows at the glacier surface (Benn et al., 2012). This leads to catastrophic damage to the downstream settlements, infrastructure and mountain ecosystems (Haritashya et al., 2018; Thompson et al., 2012). The melting of glaciers also triggers slides and avalanche falling in the glacial lake which assists the outburst of the lake which is considered a common natural hazard in the Nepal Himalayas (Shakti, 2008).

Table 3: Status of potentially dangerous glacial lakes (Khadka et al., 2019; Rounce et al., 2017)

Lake	Elevation(m)	Area (km^2)	Average expansion rate 1987 - 2016 (km^2yr^{-1})	Overall hazard
Imja Tsho	5003	32.9	0.024	Moderate hazard and risk
Tsho Rolpa	4550	49	0.005	High risk
Thulagi	4003	15.2	0.006	Moderate hazard but High risk
Barun Tsho	4530	45.8	0.038	High hazard and high risk
Lumding Tsho	4831	25.5	0.018	High risk
ChamlangTsho	4924	28.2	0.010	High risk

Imja Tsho lake have the moderate hazard and risk in the Dudh Koshi region so this indicate it do have risk to be potentially dangerous glacial lake in future (Rounce et al., 2016). The most magnificent Himalayan GLOFs occurred in the Khumbu region on 4th August, 1985, it was caused due to an ice avalanche which rumbled down the Langmoche Glacier and crashed into Dig Lake (< 25 years old lake). When the avalanche hit the lake, it released more than 1.3 billion gallons of water downstream, destroyed the almost completed Namche Small Hydro Project and extensive damage farther downstream. Similar, outburst flood occurred in 1977 at south of Mt. Ama Dablam as a result of collapse of moraine dam of the Nare Glacier lake. One of the recent GLOF from a supraglacial pond was observed in June 2016 from the Lhotse glacier (Rounce et al., 2017).

The spillway is a base-level supraglacial lake or moraine-dammed lake on the south/southeast-flowing Ngozumpa glacier in the Gokyo valley, situated between the Rowling and Khumbu valleys (Thompson et al., 2012). It has the capacity to grow into much larger moraine-dammed lake (5-6 km in length) due to its multiple sub-basins separated by debris islands which are gradually merging into a larger lake. Lake expansion and deepening could result in the millions of cubic meters of water that can potentially outburst downstream, affecting human settlements.

There is not much report of GLOF after the 2015 earthquake which suggests the stability of glacial lakes. However, GLOF events are unpredictable as the different triggering factors such as ice, snow and rock avalanching, glacier calving, moraine degradation, permafrost thawing, physical characteristics of the dam, the size and depth of lake, earthquake could result in dam failure, this will result in huge destruction of communities below the valley (Westoby et al., 2014). Similarly, the temperature rise due to the climate change also have an effect on glacial lakes as it is result of glacial melting or retreating (IPCC, 2014).

CONCLUSION AND FUTURE PERSPECTIVES

Khumbu region is one of the important regions with socio-economic importance. It is the region of Mount Everest which lures trekkers and climbers in this region. Many research works have been done in this region related to mass balance of glaciers and GLOFs as this region have the high potential GLOFs risk glacial lakes. Based on the available literature and recent studies, some of the following gaps are found to be hindered in this region which is mentioned below with the mitigations:

- Due to remoteness, steep slopes and extreme logistical difficulties, detail study on glaciers are limited and challenging.
- Lack of technical, human resource, and financial capacities.
- A careful watch/research should be given to these glaciers to minimize a natural disaster caused by GLOF.
- Government should also develop the database of spatial distribution of glaciers and make clear vision and strategy on climate change.
- More effort to be given to control GLOF in the development of water resources in the vicinity of glacierized areas in the Nepal Himalaya.
- High-resolution satellite images (such as Landsat) need to be use for the glaciological studies in Nepal such as for inventory, monitoring, mapping, and hazard prediction and detection.
- Treat the glacial lakes according to their characteristics as it is the natural storage of water at the time of scarcity of water.

- The issues of GLOF risk assessment, early warning systems and mitigation measures should be implemented to the people with awareness programs living in the vicinity of glacier.
- Formation and growth of glacial lakes need to be monitored continuously as its condition is changing yearly.
- Residents could build gabions-wire cages filled with rocks or stable barrier such as broad outwash fan to deflect the flood from settlements
- Real-time monitoring system in the high risk glacial lakes need to be implemented

References

Ageta, Y. (1993). Shrinkage of glacier AX010 since 1978, Shorong Himal, east Nepal.

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

Bajracharya, S. R., Maharjan, S. B., & Shrestha, B. R. (2010). Second generation glaciers mapping and inventory of Nepal. *Journal of Nepal Geological Society*, *41*, 21.

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

Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Guo, W., Liu, S., Immerzeel, W., & Shrestha, B. (2015). The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. *International Journal of Water Resources Development, 31*(2), 161-173.

Bajracharya, S. R., & Mool, P. k. (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology, 50*(53), 81-86.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2007). *I*mpact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan.*International Centre for Integrated Mountain Development (ICIMOD)*.

Bajracharya, S. R., & Shrestha, B. R. (2011). The status of glaciers in the Hindu Kush-Himalayan region. *International Centre for Integrated Mountain Development (ICIMOD).*

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303.

Benn, D, Wiseman, S., & Hands, K. (2001). Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. *Journal of Glaciology*, *47*(159), 626-638.

Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. I., Quincey, D., Thompson, S., Toumi, R., & Wiseman, S. (2012). Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews*, *114*(1-2), 156-174.

Bolch, T., Buchroithner, M., Pieczonka, T., & Kunert, A. (2008). Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. *Journal of Glaciology*, *54*(187), 592-600.

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

Chen, N. S., Hu, G. S., Deng, W., Khanal, N., Zhu, Y., & Han, D. (2013). On the water hazards in the trans-boundary Kosi River basin. *Natural Hazards and Earth System Sciences*, *13*(3), 795-808.

Cuellar A., & McKinney, D. (2017). Decision-making methodology for risk management applied to Imja Lake in Nepal. *Water*, *9*(8), 591.

Dyurgerov, M. B., & Meier, M. F. (1997). Mass balance of mountain and subpolar glaciers: a new global assessment for 1961–1990. *Arctic and Alpine Research*, *29*(4), 379-391.

Dyurgerov, M. B., & Meier, M. F. (2005). Glaciers and the changing Earth system: a 2004 snapshot. *Institute of Arctic and Alpine Research, University of Colorado Boulder, 58*.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., & Stoffel, M. (2014). Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods. *The Cryosphere*, *8*(6), 2313-2333.

Fujita, K., & Nuimura, T. (2011). Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences, 108*(34), 14011-14014.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., & Sharma, R. R. (2009). Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed byin situsurveys and multi-temporal ASTER imagery. *Environmental Research Letters, 4*(4).

Grove, J. M. (2004). Little ice ages: ancient and modern (Vol. 1). *Taylor & Francis*.

Hambrey, M. J., Quincey, D. J., Glasser, N. F., Reynolds, J. M., Richardson, S. J., & Clemmens, S. (2008). Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews, 27*(25-26), 2361-2389.

Haritashya, U., Kargel, J., Shugar, D., Leonard, G., Strattman, K., Watson, C., Shean, D., Harrison, S., Mandli, K., & Regmi, D. (2018). Evolution and controls of large glacial lakes in the Nepal Himalaya. *Remote Sensing, 10*(5), 798.

Hotaling, S., Hood, E., & Hamilton, T. L. (2017). Microbial ecology of mountain glacier ecosystems: biodiversity, ecological connections and implications of a warming climate. *Environmental microbiology, 19*(8), 2935-2948.

Houghton, J. (2001). Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

ICIMOD. (2011). Glacial lakes and glacial lake outburst floods in Nepal. *International Centre for Integrated Mountain Development*.

Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. *Science, 328*(5984), 1382-1385.

Immerzeel, W. W., van Beek, L. P. H., Konz, M., Shrestha, A. B., & Bierkens, M. F. P. (2012, February 01). Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change, 110*(3), 721-736.

IPCC. (014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. *IPCC*.

Jansson, P., Hock, R., & Schneider, T. (2003). The concept of glacier storage: a review. *Journal of Hydrology, 282*(1-4), 116-129.

Khadka, N., Zhang, G., & Chen, W. (2019). The state of six dangerous gla-cial lakes in the Nepalese Himalaya. *Terrestrial, Atmospheric and Oceanic Sciences, 30*, 63-72.

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

King, O., Quincey, D. J., Carrivick, J. L., & Rowan, A. V. (2017). Spatial variability in mass loss of glaciers in the Everest region, central Himalayas, between 2000 and 2015. *The Cryosphere, 11*(1), 407-426.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., & Thomas, R. H. (2007). Observations: changes in snow, ice and frozen ground.*Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.

Lutz, A., Immerzeel, W. W., Bajracharya, S. R., Litt, M., & Shrestha, A. B. (2016). Impacts of climate change on the cryosphere, hydrological regimes and glacial lakes of the Hindu Kush Himalayas: a review of current knowledge. *International Centre for Integrated Mountain Development.*

Mool, P. K., Bajracharya, S. R., & Joshi, S. P. (2001). Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region, Nepal.

Moore, R., Fleming, S., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K., & Jakob, M. (2009). Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes: An International Journal, 23*(1), 42-61.

Nuimura, T., Fujita, K., Yamaguchi, S., & Sharma, R. R. (2012). Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu region, Nepal Himalaya, 1992-2008. *Journal of Glaciology, 58*(210), 648-656.

Oerlemans, J. (2001). Glaciers and climate change. *CRC Press*.

Pritchard, H. D. (2017). Asia's glaciers are a regionally important buffer against drought. *Nature, 545*(7653), 169.

Quincey, D., Richardson, S., Luckman, A., Lucas, R. M., Reynolds, J., Hambrey, M., & Glasser, N. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change, 56*(1-2), 137-152.

Rai, S. C. (2005). An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China. *WWF Nepal Program*.

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International, 65*, 31-47.

Rounce, D. R., Byers, A. C., Byers, E. A., & McKinney, D. C. (2017). Brief communication: Observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. *The Cryosphere, 11*(1).

Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C., & Watson, C. S. (2016). A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. *Hydrology and Earth System Sciences, 20*(9), 3455.

Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E., Cristofanelli, P., Stocchi, P., Agrillo, G., & Ma, Y. (2015). Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt. Everest (central Himalaya) in the last 2 decades (1994–2013). *The Cryosphere, 9*(3), 1229-1247.

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

Shakti, P. (2008). Flash floods due to glacier lake outburst floods in the mountainous regions of Nepal: A case study of Kawache Glacier Lake outburst flood. *Water and Urban Development Paradigms: Towards an Integration of Engineering, Design and Management Approaches*, 329.

Shakti, P., Pradhananga, D., Ma, W., & Wang, P. (2013). An Overview of Glaciers Distribution in the Nepal Himalaya. *Hydro Nepal: Journal of Water, Energy and Environment, 13*, 20-27.

Shrestha, A. B., Wake, C. P., Dibb, J. E., & Mayewski, P. A. (2000). Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 20*(3), 317-327.

Shrestha, A. B., Wake, C. P., Mayewski, P. A., & Dibb, J. E. (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, D. P., & Zinck, J. A. (2001). Land use classification in mountainous areas: integration of image processing, digital elevation data and field knowledge (application to Nepal). *International Journal of Applied Earth Observation and Geoinformation*, *3*(1), 78-85.

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

Thompson, S. S., Benn, D. I., Dennis, K., & Luckman, A. (2012). A rapidly growing moraine-dammed glacial lake on Ngozumpa Glacier, Nepal. *Geomorphology*, *145*, 1-11.

Ueno, K., Toyotsu, K., Bertolani, L., & Tartari, G. (2008). Stepwise onset of monsoon weather observed in the Nepal Himalaya. *Monthly Weather Review*, *136*(7), 2507-2522.

Venkatachalam, S., & Prabagaran, S. R. (2015). Comparative assessment of bacterial communities from Himalayan mountains of Nepal and India. *ENVIS Bulletin Himalayan Ecology*, *23*, 09.

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

Watson, C. S., Quincey, D. J., Carrivick, J. L., & Smith, M. W. (2016). The dynamics of supraglacial ponds in the Everest region, central Himalaya. *Global and Planetary Change*, *142*, 14-27.

Watson, C. S., Quincey, D. J., Carrivick, J. L., & Smith, M. W. (2017). Ice cliff dynamics in the Everest region of the Central Himalaya. *Geomorphology*, *278*, 238-251.

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J., & Reynolds, J. M. (2014). Modelling outburst floods from moraine-dammed glacial lakes. *Earth-Science Reviews*, *134*, 137-159.

Whiteman, C. D. (2000). Mountain meteorology: fundamentals and applications. *Oxford University Press*.

Williams, R. S., Ferrigno, J. G., & Manley, W. (2010). Glaciers of Asia. *US Geological Survey Professional Paper,* 349.

Xu, B., Cao, J., Hansen, J., Yao, T., Joswia, D. R., Wang, N., Wu, G., Wang, M., Zhao, H., & Yang, W. (2009). Black soot and the survival of Tibetan glaciers. *Proceedings of the National Academy of Sciences, 106*(52), 22114-22118.

Zhang, G., Yao, T., Shum, C., Yi, S., Yang, K., Xie, H., Feng, W., Bolch, T., Wang, L., & Behrangi, A. (2017). Lake volume and groundwater storage variations in Tibetan Plateau's endorheic basin. *Geophysical Research Letters, 44*(11), 5550-5560.

Zhang, G., Yao, T., Xie, H., Wang, W., & Yang, W. (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.

Tina Rai

Conflicts of Interest

There are no conflicts to declare.