INTERNATIONAL JOURNAL OF ENVIRONMENT

Volume-9, Issue-1, 2019/20 ISSN 2091-2854

Received:13 October 2019 *Revised:25 January 2020* *Accepted:30 January 2020*

MONITORING SUPRAGLACIAL LAKES FORMATION AND RISK OF OUTBURST FLOODING IN THE HIMALAYAN CRYOSPHERE OF PAKISTAN

Arshad Ashraf* and Manshad Rustam

Climate, Energy and Water Research Institute

National Agricultural Research Center (NARC), Park road, Chakshahzad, Islamabad, Pakistan

*Corresponding author: mashr22@yahoo.com

Abstract

The dramatic rise in warm temperatures in the Himalayan region has caused the formation and expansion of numerous supraglacial lakes, some of which pose a serious flood hazard for the downstream communities. In this study, we have investigated the risk of flood hazards associated with supraglacial lakes in the Hindu Kush, Karakoram and Himalayan ranges of Pakistan using Landsat 8 OLI (Operational Land Imager) data of 2013 and field observations. Among the total of 438 supraglacial lakes, the majority were identified in the Karakoram (378) followed by the Hindu Kush range (39). The concentration of lakes was high within 3500-4000 m elevation (168) followed by 4000-4500 m elevation range (116). The lakes had shown more than a two-fold increase during the 2001-2013 period in the three mountain ranges. The increase in lake number was pronounced over valley glaciers likely due to increasing hydro-glacial activity under changing climate. Two types of supraglacial lakes were identified based on geographic characteristics, for example those rolling over glaciers surface away from the margins (called rolling supraglacial lakes 'RSLs') and the lakes found near the margins of glaciers mostly stationary in nature (called static supraglacial lakes 'SSLs'). Most of the glacial lakes outburst flood (GLOF) events have been observed from SSLs in this region. However, the hydrodynamic process exaggerating the risk of GLOF from supraglacial and englacial lakes needs in-depth research for effective disaster risk reduction in this region in future.

Key words: Climate change; Himalaya; Hindu Kush; Karakoram; Supraglacial lake

DOI: http://dx.doi.org/10.3126/ije.v9i1.27587

Introduction

The rapid retreat of glaciers, increasing number of melt-water lakes and the resulting catastrophic floods are the true indicators of climate change in the Himalayan cryosphere of South Asia. Monitoring of glacial lakes is gaining importance in context of growing risks of glacial lakes outburst flood (GLOF) as a key climate change hazard in the Himalayan region. Assessment of such flood hazards and knowledge of environmental processes are key factors in flood risk management in the downstream (Kamble et al., 2013; Shrestha, 2019). Glacier retreat observed in most of the Hindu Kush and Himalaya regions (Bolch et al., 2012), has resulted in formation numerous glacial lakes including supraglacial ones. The frequency of GLOF events has been increased in the Hindu Kush-Himalayan region since the second half of the 20th century due to the combined effects of climate change and deforestation (Iturrizaga et al., 2005; Sakai and Fujita, 2010; Khan, 2014). Many such events have been reported from supraglacial and englacial lakes outbursting in the Hindu Kush-Karakoram-Himalaya (HKH) region of Pakistan (Table 1), which had resulted in loss of the valuable lives, property and infrastructure in the downstream (DRM, 2013; Ashraf et al., 2014; ICIMOD, 2015; Ashraf et al., 2017). According to Inter Press Service (2015), Pakistan has experienced seven GLOFs over the past 17 months alone that not only wiped out standing crops and irrigation networks but also displaced local communities. This situation could be worsened as temperature rise and extreme weather conditions are predicted in the coming decades in the HKH cryosphere of Pakistan, prompting an urgent need for greater preparedness at all levels of society.

Remote sensing (RS) techniques have been successfully applied to study the behavior of supraglacial lakes in various regions of the world (Reynolds, 2000; Richardson and Reynolds, 2000; Benn et al., 2001; Wessels et al., 2002; Sundal et al., 2009; Sakai and Fujita, 2010; Wang et al., 2011). Small supraglacial lakes in a majority of cases are not hazardous, but they may generate surprisingly large floods that represent hazards at local scales (Richardson, 2010). The situation demands better risk assessment of GLOF hazards as the local communities are now more vulnerable to the increase in frequency of those hazards due to the unprecedented rise in global warming in this region.

This paper is aimed to analyze the formation of supraglacial lakes and the risk of outburst flood hazard in the HKH region of Pakistan (Figure 1) using Landsat ETM+/OLI image data of 2001-2013 period coupled with ground information. The region stretches over an area of about 121,724 km^2 of which 32.3% area is contributed by the Hindu Kush, 40.1% by the Karakoram and 27.6% by the Himalaya range. It forms a part of the Upper Indus Basin (UIB) containing 10 sub-basins, the distribution of which is shown in Figure 1. Climate in this cryospheric region is mostly semi-dry to dry with annual rainfall ranging between 200 and 500 mm in the valleys (Khan, 2014). Monsoon rainfalls are higher during July-September period, especially in the southern basins, while the westerly fronts originating from the Mediterranean region during winter and spring seasons dominate most of the upper region.

Table 1. Flood events occurred from Supraglacial/englacial lakes out-bursting in various parts of the HKH region.

Period	**Description**	**Source**
April 2007	High water discharge from Ghulkin glacier, upper Hunza valley	Ashraf et al. 2014
April 2008	Flooding from Ghulkin glacier resulted in loss of the property and infrastructure	Ashraf et al. 2014
June 2008	Sudden discharge from Ghulkin glacier resulted in loss of the property and infrastructure	Ashraf et al. 2014
March 2009	Sudden discharge from Ghulkin glacier	ICIMOD, 2015
July 2010	High water discharge from Ghulkin glacier resulted in loss of the property and infrastructure	ICIMOD, 2015
2010	▪ Una Glacial burst caused damages to natural forest and the settlements of Sat, Dart, Ghosonar, Chira and Bulchi villages in Bagrot valley. ▪ Lake outburst over Hinarchi glacier caused heavy damage to natural forest and agricultural land of villages Khama, Bulchi and Chira. Damages occurred to natural forest as well as settlements of Taisote and Massingot villages due to Dubani Glacier/lakes burst in Bagrot valley.	DRM, 2013
December 2011	Flood water destroyed the fields in Ghulkin	ICIMOD, 2015
July 2012	Extensive discharge from Yaz-Sam lake	ICIMOD, 2015
June 2013	High water discharge resulted in loss of the nearby property	ICIMOD, 2015
July 31, 2013	Flood in Reshun valley severely affected infrastructure, property and livelihoods in Chitral	Ebrahim, 2013
August 2013	Extensive water discharge resulted in loss of the property/infrastructure	ICIMOD, 2015
April 2014	High water discharge triggering flash flood in the Bagrot valley	Shaikh & Tunio, 2015
July 2015	Extensive water discharge creating flood condition in Bagrot valley	Shaikh & Tunio, 2015

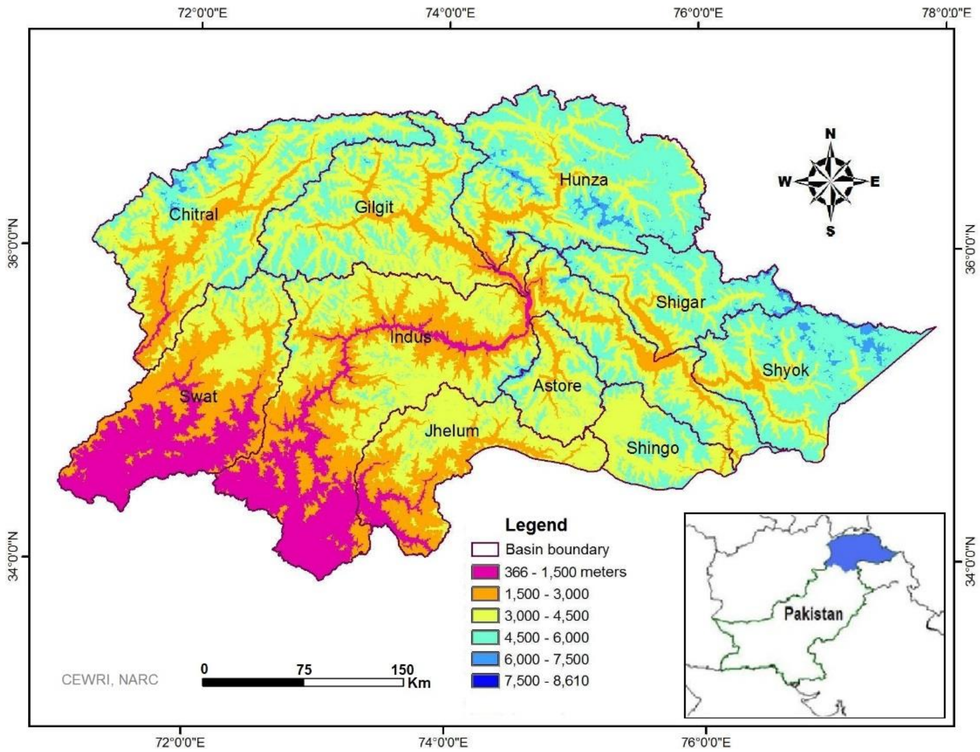

Figure 1. Location of HKH ranges and 10 river basins in the Upper Indus Basin of Pakistan

Materials and methods

Remote sensing (RS) data of Landsat 8 OLI (Operational Land Imager) of the 2013 period was downloaded from the web link (http://glovis.usgs.gov) for mapping and analyses of supra-glacial lakes within 10 river basins of the three HKH ranges. Landsat 7 ETM+ (Enhanced Thematic mapper plus) images of 2001 and 2009 were downloaded for temporal analysis of supraglacial lakes in Hunza river basin. Remote sensing application in GLOF risk assessment usually involves detection and mapping of glaciers and glacial lakes, studying impoundments and their surroundings (Richardson, 2010). The RS analysis was supplemented by available topographic maps of 1:50,000 and 1:250,000 scales published by Survey of Pakistan. Digital elevation model (DEM) data of Shuttle Radar Topography Mission (SRTM) 90 m was downloaded from www.jpl.nasa.gov/ in order to study the vertical distribution of lakes in the study area,

Supraglacial lakes were detected and mapped on cloud- and snow-free images through visual interpretation and analysis. The lakes' boundaries were delineated basin-wise through on-screen digitization of the image data. In order to minimize the uncertainty in the boundary demarcation, the threshold value of 0.1 ha was considered for delineating lakes to eliminate numerous small supraglacial ponds scattered over the glacier surface. Glacial lakes were first tried to identify using Normalized Difference Water Index (NDWI), but the automated technique was not considered appropriate for detection of supraglacial water bodies over debris-covered glaciers from many other glacier facies like silty/dusty ice, debris-covered ice or steep crevasses for mapping and analysis (Rivera et al., 2007). This indexing method is mostly used for delineation of flood extent in an area or distinguishing open water bodies from the soil in plain areas (Huggel et al., 2002). Lakes attribute data like location coordinates, area, length, and elevation were determined in each river basin using analytical functions of Geographic information system (GIS). The location of lakes was marked clock-wise in each basin and stored in geographic coordinates (longitude, latitude) with a unique identifier number in point data file. The length of lakes was measured along the direction of flow of their mother glacier. The lake elevation was determined through overlaying point data over DEM and using extract values function of the ArcGIS software.

The decision criteria adopted to define potential hazards of glacier lakes includes lake area; the rate of lake growth; characteristics of mother glacier and surrounding geometry. Temporal analysis of the lakes was performed to assess the rate of change using image processing and GIS techniques. The relationship of supraglacial lakes was studied with the glacier area of 2013 period (GIP, 2017). The strength and confidence level of the linear relationship between the two variables were studied using the coefficient of determination 'R^2' and Pearson coefficient '*p*'.

Results and discussion

A total of 438 supraglacial lakes were identified in the HKH region of Pakistan during the 2013 period, among which 378 were found in the Karakoram, 39 in the Hindu Kush and 21 in the Himalaya range (FTR, 2015). The situation indicates the presence of less extensive snow and ice coverage in the Hindu Kush and the Himalayas ranges as compared to the Karakoram range. The low dense coverage and further depletion of glacial ice mass in the Hindu Kush and Himalayas may be attributed to warming conditions in these regions (Azam et al., 2018; Ashraf and Batool, 2019; Wester et al., 2019). The rise in temperature may also influence the precipitation pattern from snowfall to rain (Bajracharyra, et al., 2014), which affects the glacier accumulation amount resulting in loss of ice mass in the Himalayas. About 93% of lakes (407) fall in the areal category of <2 ha, 5.5% (24) in the 2–5 ha and 0.9% (4) in the 5–10 ha category. The lakes of >10 ha category (3) were identified mainly in the Karakoram range (Figure 2). Small size lakes (<2 ha) were found 350 in the Karakoram range, 36 in the Hindu Kush and 21 in the Himalaya range (Figure 3). The elevation has also influenced the development of lakes. The lakes were highest in number below 4000 m elevation, whereas they were found least above 4500 m elevation (Figure 4), likely due to cooler temperatures and presence of general accumulation condition of the glaciers at higher altitudes. In most cases, the glacier ice mass residing above 4500 m elevation, like in the Karakoram range, is in steady condition. The lakes were identified maximum within 3500-4000 m elevation in Hunza (90), Shigar (29), Astore (6), Jhelum (4) and Chitral (12) river basins. In Gilgit basin, the lakes were found within 3000-3500 m (7), while in Swat, they were maximum within 4000-4500 m range (4). The vertical distribution of supraglacial lakes over glacial ice mass differentiates, in general, the accumulation and ablation zones of the glacier, i.e. ablation zone with the presence of extensive lakes/ponds and the accumulation lacking those. But in case of ablation zone over steep slope, as in the Karakoram, where the glaciers have some of the steepest gradients in the world (e.g. avalanche fed Minapin glacier beneath the Rakaposhi peak (7788 m) descends from about 5300 m to 2400 m elevation over a distance of only 10 km (29% slope)), the lake numbers are not pronounced. The parts of glaciers over steeper slopes are usually highly active and contain dense crevasses where supraglacial melt found no resident time and seeps down readily to join englacial channel flows.

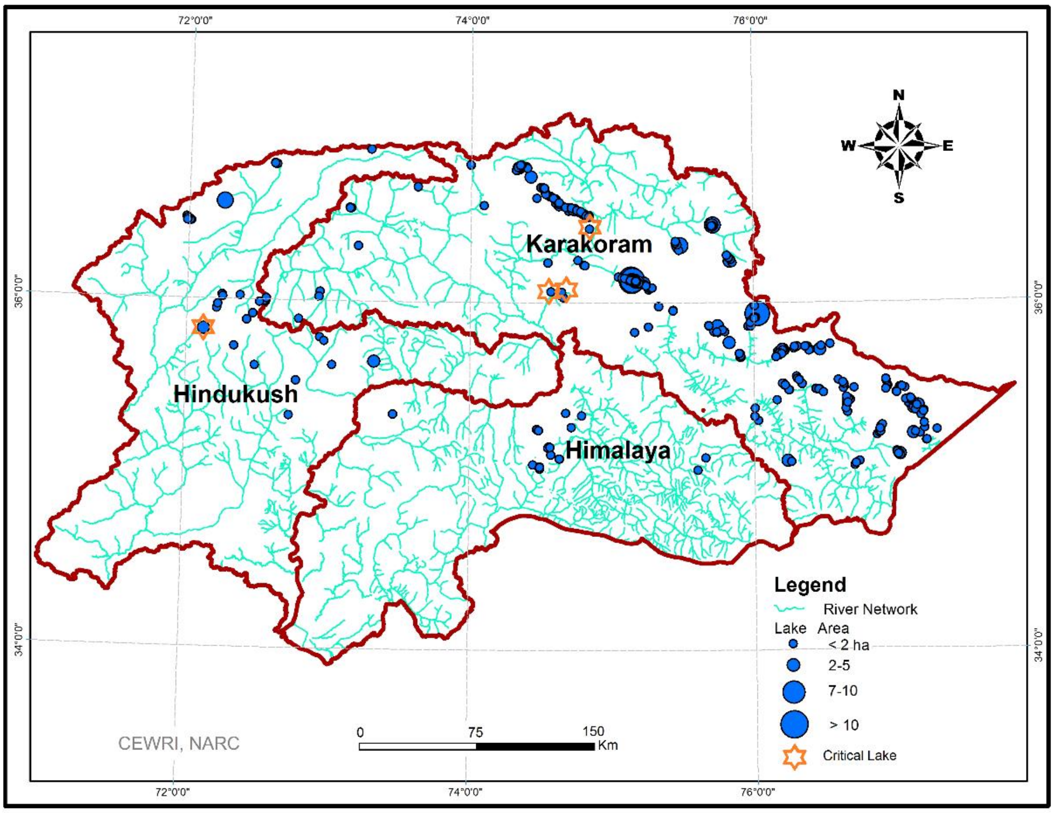

Figure 2. Distribution of various area classes of supraglacial lakes and critical lakes in the HKH region

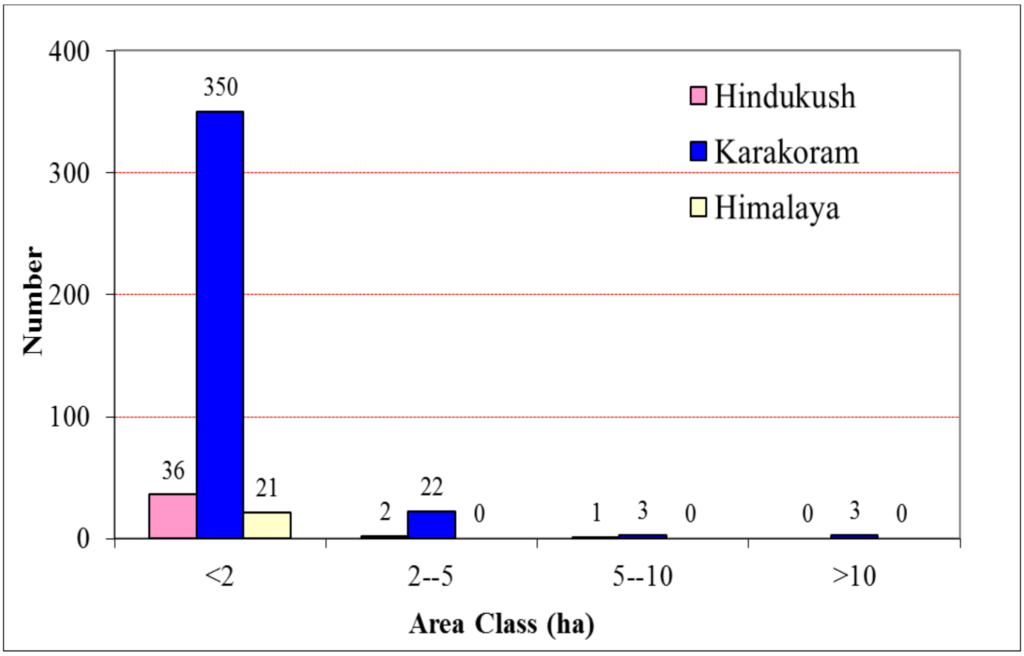

Figure 3. Comparison of various area classes of supraglacial lakes in the HKH ranges

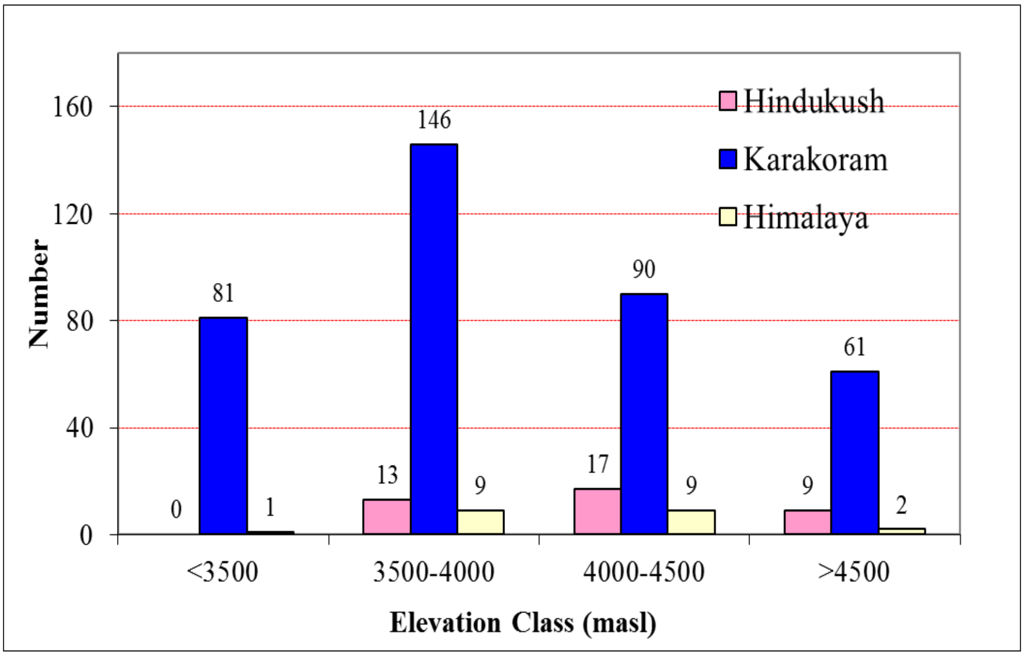

Figure 4. Comparison of glacial lakes at various elevation classes in the HKH ranges

In comparison to the lake inventory of 2001 (Ashraf et al., 2012), the supraglacial lakes have shown an increase in all the HKH ranges, i.e., from 197 in 2001 to 438 in 2013. The increase in lake number appears to be higher in Hunza, Shyok and Shigar river basins of the Karakoram and Chitral river basin of the Hindu Kush range. Most of the medium and large-sized valley glaciers lie in these basins. In the Hindu Kush, a high concentration of valley glaciers exists in the Chitral basin, therefore supraglacial lakes are also extensive in number in this basin. The lake number and glacier area of 2013 period exhibited a close positive relationship

(R^2=0.77) significant at $p<0.05$. Similarly, the lake number indicated a fair positive correlation with valley glaciers (R^2=0.62). The bulk of ice mass in different river basins is contributed by the large sized valley glaciers like Batura, Biafo, Hispar, Baltoro, and others in different HKH basins. The lakes are mostly found at elevations where glacier ice mass is present in abundance. Glimpses of some of the supraglacial lakes formed over various valley type glaciers are shown in Figure 5. The lake formed over Ghulkin glacier in the Hunza basin has breached several times in the past causing heavy water discharge mixed with debris. The large-sized supraglacial lakes are developed through temporary or permanent blockage of subsurface water conduits that move with glaciers as long as they find some escape point. The number of supraglacial lakes was higher (>60) in three glaciated basins of the Karakoram, i.e. Hunza, Shigar and Shyok. Numerous small ponds and lakes formed over Baltoro glacier in Shigar basin provide a clue of growing warm conditions in lower valleys of the basin (Figure 5).

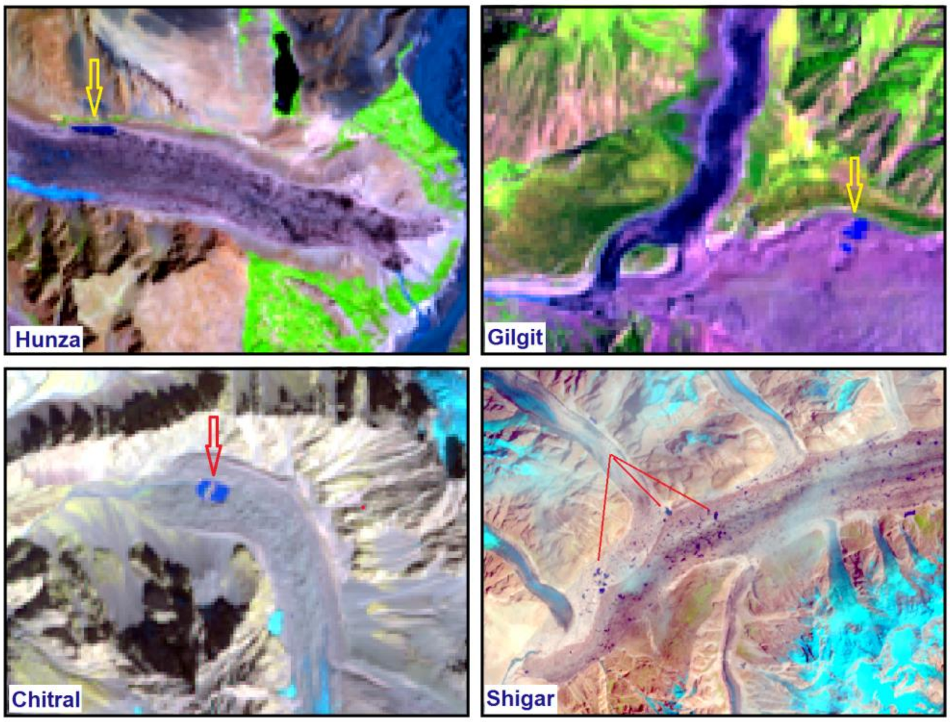

Figure 5. Glimpses of supraglacial lakes formed in different HKH basins (2013)

Generally two types of supraglacial lakes were observed based on their mobility characteristics on glaciers in this region, i.e. those rolling over glacier surface away from the glacial margins (called rolling supraglacial lakes –RSLs) and the lakes exist near the margins of glacier – mostly stationary in nature (called static supraglacial lakes–SSLs). The RSLs have the property of splitting and merging with neighboring lakes during the movement of glaciers. In the basins like Hunza, Shigar and Shyok, where large valley glaciers descend in the temperate zone, results in exaggerating the ice melting process over glaciers that favors formation/expansion of supraglacial ponds/lakes. The rate of glacier drift can be measured through assessing the movement of RSLs usually through analysis of time-series image data (Figure 6). An increase in lake number from 126 to 225 (aggregate lake area from 238 ha to 283 ha) was observed on Hispar glacier in the Hunza basin during 2001-2013 period (Table 2). As all lakes were not sustained such a long time, so from the movement of selected RSLs that remained during 2001-2009 period, adrift in the surface of Hispar glacier was estimated at the rate of about 18 m y^{-1}.

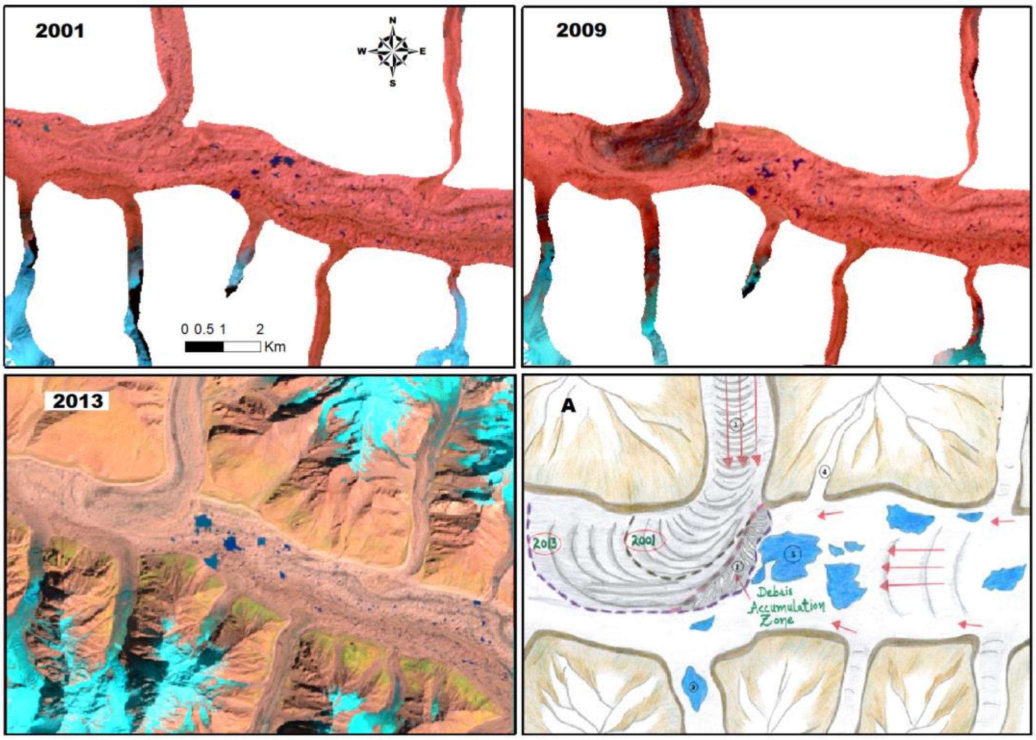

Figure 6. Temporal variation in supraglacial lakes rolling over Hispar glacier in the Hunza basin during 2001-2013 period

SSLs have the property of filling and breaching owing to blockage of internal conduits of a glacier, i.e. they fill rapidly due to the conduit blockage, sustain for days until the blocking material breached. The recharge to these lakes is mainly from snow and ice melt, the downpour of liquid precipitation and flows from surface/subsurface channels. Most of the outburst flood events have been reported from SSLs in this cryospheric region (e.g. DRM, 2013; ICIMOD, 2015; Ashraf et al., 2017). Glimpses of few SSLs that have caused frequent flooding events in the recent past are shown in Figure 7. Both types of the lake can be differentiated from the visual interpretation and temporal analysis of the image data.

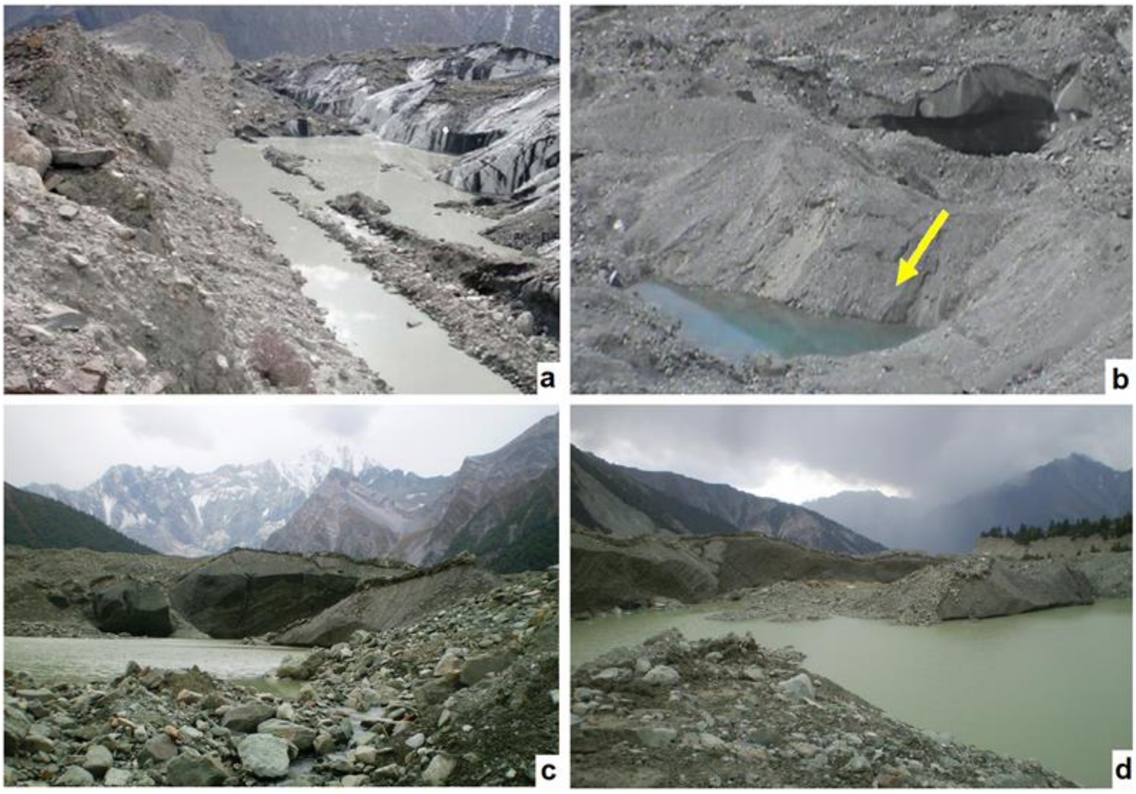

Figure 7. A supraglacial lake formed over Ghulkin glacier in Hunza valley during 2008 possesses history of fill and breach (Dawn, 2008) (a). The remnant of a supraglacial lake- *Barberi* formed over Hinarchi glacier, Gilgit basin after breaching (Photo courtesy: Zahid Hussain) (b); A supraglacial lake is growing rapidly within heavy debris of the Gargo glacier in Gilgit basin since last decade (Surveyed in September, 2013) (c and d)

Table 2. Temporal variations in Supraglacial lakes (number and area) over Hispar glacier in the Hunza basin (2001-2013).

Year	Lakes identified	Surface Area (ha)	
		Range	Total
2001	126	0.72–11.79	238.16
2009	150	0.68–15.42	253.91
2013	225	0.68–21.02	282.73

There were 4 supraglacial lakes identified as potentially dangerous in the 2013 lake inventory, which lies mainly in Chitral, Gilgit and Hunza river basins (Table 3 and few are shown in Figure 5). The reasons for characterizing those lakes critical were rapid growth in lake area (detected from temporal image analysis) and history of periodic filling and breaching in the past. Two of those critical lakes fall in the Central Karakoram National Park (CKNP) (Senese et al. 2018). The supraglacial lakes identified in the Hunza and Gilgit basins had caused frequent flooding events in the recent past. An ephemeral lake Hunz-gl 14 (locally '*Yaz-Sam*') over Ghulkin glacier in the Upper Hunza valley (Figure 7a) had caused frequent flooding events during 2008, 2010, 2013 and 2015 owing to its geographic position near the highly crevassed part of the glacier (Ashraf et al., 2014, 2017). Those events have resulted in heavy damage to the property and infrastructure in nearby Ghulkin and Hussaini villages. The empty lake measured on August 16, 2008 (nearly two months after its breach) was 221 m in length, 12 m in width and 7 m in depth (Ashraf et al., 2011). The lakes caused GLOFs owing to factors like rapid increment in lake water because of snow/ice melting, overflown of subglacial channels and heavy rainfall/surface runoff. This is evident from the fact that most of the events occurred during April to August months – the snow melting and ablation periods representing spring and summer seasons pointing towards high supraglacial lake activity under warm conditions.

Table 3. Supraglacial lakes identified as potential GLOF lakes in the HKH region of Pakistan

S.No.	Lake Number	Area (ha)	Length (m)	Elevation (m)	Remarks
1	Chi-gl 108	4.94	308	3669	Growing over glacier terminus
2	Gil-gl 656	0.29	143	2867	History of fill and breach
3	Gil-gl 658	1.95	205	3297	Growing over glacier terminus
4	Hunz-gl 14	1.39	226	2876	History of fill and breach

Where Chi-gl =Chitral glacial lake, Gil=Gilgit, Hunz=Hunza

Similarly, an ephemeral lake Gil-gl 656 (locally named '*Barberi*') developed over Hinarchi glacier (Figure 7b) possesses a history of outburst flooding damaging the valuable forest, agricultural land and the property of nearby Sat village in Bagrot valley of Gilgit basin. The profile of this lake was measured using ground-penetrating radar (GPR 250 MHz shielded antenna) by a team of CEG department of Peshawar University in 2012. According to their findings, the lake about 25 m in length contained fresh debris underlain by old debris/moraines in the bottom ranging in depth from 2.3 m to >15 m. Both the lakes, i.e. Hunz-gl 14 and Gil-gl 656 lie at more or less similar altitudes in the temperate zone below 3000 m elevation (Table 3). Similarly, a supraglacial lake Gil-gl 658 growing at the rate of about 0.27 ha y^{-1} since 2006 at elevation of about 3297 m over Gargo glacier in Bagrot valley (Figures 7c&d) breached suddenly in September 2014. According to a team of PMD visiting the lake site next month of that event, the local people had heard a roaring sound during the time of the draining process of the lake. It is assumed that a subglacial activity like a sudden breach of a choking conduit had provided an outlet to lake water to escape swiftly. Structural glaciology (e.g. crevasses, cavities) is responsible for some supraglacial derived debris reaching the subglacial system (Benn et al., 2012). The debris and the detached ice mass usually blocks the englacial conduits forming englacial lakes incases. Because of high sliding velocities, isothermal ice produces large volumes of meltwater, which flows out from englacial channels of glacier (Figure 8). The breaching of the englacial lake under the immense pressure of ice-melt water releases energy and causes the lowering down of the stored water from the linked supraglacial pond/lake. The activity may be sudden or takes weeks sometimes months based on the structural glaciology and characteristics of the blocking material in the englacial conduits.

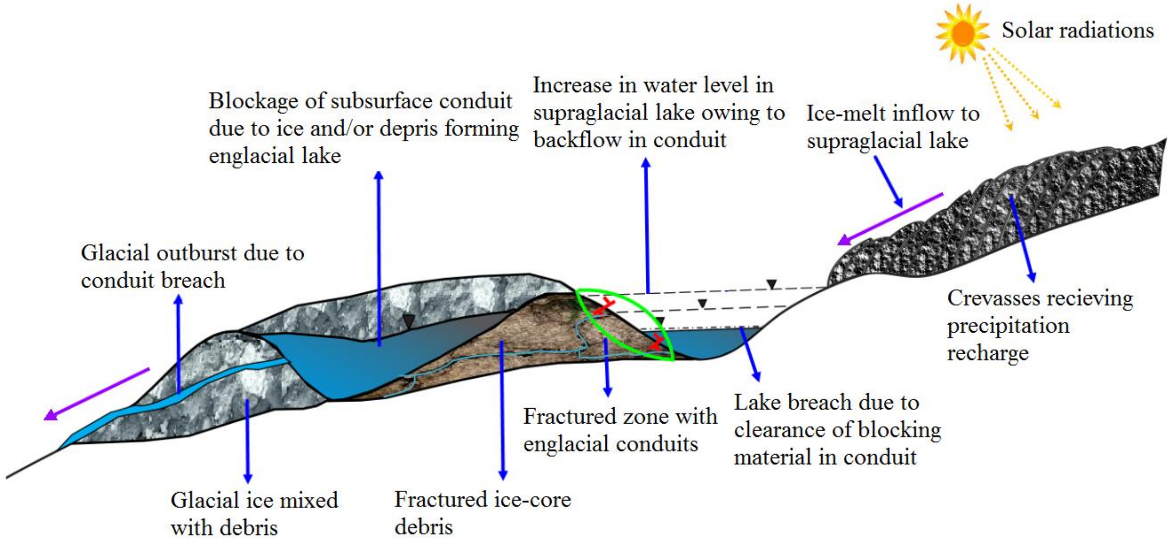

Figure 8. Glacio-hydrodynamic processes causing filling and breaching of supraglacial lakes in the region

The monitoring of supraglacial lakes is usually conducted by local communities and NGOs through assessment of the current situation and new features development over glacier; transit walks; visual observations, Measurements using apparatus and marking of iron pegs to monitor the movement. The critical supraglacial lakes formed over Ghulkin glacier, e.g. *Roud, Ghoze, Borith, and Yaz-Sam* are being monitored since 2006 in the upper Hunza valley (ICIMOD, 2015). In cases, it is difficult to segregate flooding from supraglacial and englacial lakes, as breaching of both these lakes is often related to direct outbursting of glaciers. Some of the examples are glacial outburst flooding in Reshun valley on July 31, 2013; in Boni during 2011; in Bindo Gol during 2010; in Sonoghor valley during 2007; on Rakaposhi glacier during 2007 and in Yarkhon Lasht during 2003. Due to remoteness of the source glaciers, these floods are assumed to occur from the collapse of supraglacial/englacial lakes because of a sudden influx of water from other sources in the drainage conduits or sudden earthquake/seismic activity. According to the locals, disasters cannot be stopped fully but their risks can be minimized. Therefore, long term planning and coordinated efforts are essential to reduce disaster risks and vulnerabilities in this region.

Conclusions

In the present study, we have investigated the risk of flood hazards associated with supraglacial lakes in the three HKH ranges of Pakistan using remote sensing technique coupled with field observations. The frequent GLOF events occurred over the last two decades in this cryospheric region have impacted the livelihood of numerous local communities in the downstream. Those events are mostly associated with supraglacial/englacial lakes outbursting under rapid changes in the climate and glacier environment of the region. The supraglacial lakes had shown more than two-fold increase during 2001-2013 period in the HKH ranges. The increase in concentration of the lakes in has exaggerated the risk of outburst flooding hazard in the downstream as evident from increase in occurrence of GLOF events in the recent decades in this region. The exact source of flooding and differentiation between supraglacial and englacial lakes outburst flooding are sometimes difficult to assess due to remoteness of the event source in various parts of the HKH region. Generally, such flood events have been assumed to occur from glacial out-bursting caused by growing warm conditions. Two types of supraglacial lakes were observed based on the location characteristics, i.e. those rolling over glacier surface (called rolling supraglacial lakes 'RSLs'), mostly found away from the glacial margins, and the others found close to margins of glaciers mostly stationary in nature (called static supraglacial lakes 'SSLs'). The latter lakes were found hazardous as most of the GLOF events have been observed from those lakes in various HKH basins. Integrated risk management efforts based on effective awareness, preparedness and early warning measures are needed on a sustainable basis to cope with negative impacts of such climate-induced hazards in this region in future. It is often difficult to detect such sub-glacial developments in conduits and formation of englacial lakes using remote sensing techniques. Such phenomena can be better understood if investigated by adopting isotope methods in glacial hydrology. The role of temperature and precipitation in supraglacial formation is complex and difficult to describe because of limited high altitude data availability in the glacial watersheds.

Acknowledgments

The database development and mapping support by the GIS team of National Agricultural Research Centre and Quaid-i-Azam University, Islamabad is highly acknowledged. We are also thankful to the Editor and two anonymous reviewers for rendering valuable comments for improving this paper.

References

Ashraf, A., Batool, A., 2019. Evaluation of glacial resource potential for sustaining kuhl irrigation system under changing climate in the Himalayan region. Journal of Mountain Science 16(5), 1150–1159. DOI: 10.1007/s11629-018-5077-0

Ashraf, A., Naz, R., Iqbal, M.B., 2017. Altitudinal dynamics of glacial lakes under changing climate in the Hindu Kush, Karakoram, and Himalaya ranges. *Geomorphology,* 283, 72–79. DOI: https://doi.org/10.1016/j.geomorph.2017.01.033

Ashraf, A., Nazi, R., Roohi, R., 2012. Glacial lake outburst flood hazards in Hindu Kush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis, *Geomatics, Natural Hazards and Risk*, 3(2), 113–132. DOI: https://doi.org/10.1080/19475705.2011.615344

Ashraf, A., Roohi, R., Nazi, R., Mustafa, N., 2011. Identification of Glacial Flood Hazards in Karakoram Range Using Remote Sensing Technique and Risk Analysis. *Journal of COMSATS- Science Vision*, Vol.16 and Vol. 17, 71–80.

Ashraf, A., Roohi, R., Nazi, R., Mustafa, N., 2014. Monitoring Cryosphere and Associated Flood hazards in High Mountain Ranges of Pakistan using Remote sensing technique, *Natural Hazards*, 73, 933–949. DOI: 10.1007/s11069-014-1126-3

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. DOI: https://doi.org/10.1017/jog.2017.86

Bajracharyra, S.R., Maharjan, S.B., Shrestha, F., 2014. The status and decadal change of glaciers in Bhutan from 1980 to 2010 based on satellite data. *Annals of Glaciology* 55(66), 159–199.

Benn, D., Benn, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., 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, 156–174. DOI: https://doi.org/10.1016/j.earscirev.2012.03.008

Benn, D.I., Wiseman, S., Hands, K.A., 2001. Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. *Journal. Glaciol.*, 47, 626–638. DOI: https://doi.org/10.3189/172756501781831729

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, G., Frey, H., Kargel, J., Fujita, K., Scheel, M., Stoffel, M., Samjwal, B., 2012. The state and fate of Himalayan glaciers. *Science*, 336, 310–314. DOI: 10.1126/science.1215828

Dawn, 2008. Glacier burst floods vast area in Hunza. http://www.dawn.com/news/304405/glacier-burst-floods-vast-area-in-hunza (Accessed on 6.08. 2014).

DRM, 2013. Report on Community based Disaster Risk Management in Bagrote, GLOF field office, Gilgit, Pakistan. p 18.

Ebrahim, Z.T., 2013. Flash floods wash away livelihoods in Chitral. http://www.thethirdpole.net/ (Accessed on 3.07. 2014).

FTR, 2015. *Updating GLOF lake inventory of Northern Pakistan & establishment of community based early warning system in Bagrot and Bindogol Valleys (for Pakistan GLOF Project).* Final Technical Report of Pakistan Agricultural Research Council (PARC), Pakistan Meteorological Department (PMD), Ministry of Climate Change, UNDP & Adaptation Fund (AF). p 130.

GIP, 2017. *Glacier inventory of Pakistan*. SUPARCO, Institute of Tibetan Plateau Research (ITP), Chinese Academy of Sciences. p 124.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotech Journal* 39, 316–330. DOI: https://doi.org/10.5167/uzh-63230

ICIMOD, 2015. Presentation on Monitoring of Ghulkin glacier. Focus Huminatarian Assistance in ICIMOD Workshop 28-30 Jan. 2015, Kathmandu, Nepal. p 16.

Inter Press Service, 2015. In the Shadow of Glacial Lakes, Pakistan's Mountain Communities Look to Climate Adaptation. http://www.ipsnews.net/2015/01/. (Accessed on 2.12. 2019).

Iturrizaga, L., 2005. New observations on present and prehistorical glacier-dammed lakes in the Shimshal valley (Karakoram Mountains). *Journal of Asian Earth Sciences*, *25*(4), 545–555. DOI: 10.1016/j.jseaes.2004.04.011

Kamble, R., Walia, A., & Thakare, M. (2013). Ecosystem Approach To Flood Disaster Risk Reduction. *International Journal of Environment*, *2*(1), 70–82. DOI: https://doi.org/10.3126/ije.v2i1.9209

Khan, M.I., 2014. GLOF Risk Reduction Guidelines for Gilgit-Baltistan Pakistan. Pakistan Glacial Lake Outburst Floods (GLOF) Project, Climate Change Division, Islamabad. p 50.

Reynolds, J.M., 2000. On the formation of supraglacial lakes on debris-covered glaciers. In proceedings of a workshop held at Seattle, Washington, USA, September 2000. IAHS Publ. no. 264.

Richardson, S.D. and Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. *Quaternary International*, 65–66, 31–47. DOI: https://doi.org/10.1016/S1040-6182(99)00035-X

Richardson, S.D., 2010. Remote sensing approaches for early warning of GLOF hazards in the Hindu Kush-Himalayan region, Final report-ver 1.2, United Nations *International Strategy for Disaster Reduction* (UN/ISDR).

Rivera, A., Benham, T., Casassa, G., Bamber, J., Dowdeswell, J., 2007. Ice elevation and areal changes of glacier from Northern Patagonia Icefield, Chile. *Global and Planetary Change,* 59, 126–137. DOI: https://doi.org/10.1016/j.gloplacha.2006.11.037

Sakai, A. and Fujita, K., 2010. Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya. *Journal of Glaciology,* 56, 177–181. DOI: https://doi.org/10.3189/002214310791190785

Senese, A., Maragno, D., Fugazza, D., Soncini, A., et al. 2018. Inventory of glaciers and glacial lakes of the Central Karakoram National Park (CKNP – Pakistan). *Journal of Maps*, 14:2, 189–198, DOI: 10.1080/17445647.2018.1445561

Shaikh, S., Tunio, S., 2015. Mountain Pakistan walls off glacial lake flash floods. https://af.reuters.com/article/idAFL8N14G0IB20151227 (Accessed on 2.12. 2019).

Shrestha, B.B., 2019. Assessment of Flood Hazard and Agriculture Damage under Climate Change in the Bagmati River Basin of Nepal. *International Journal of Environment*, 8(2), 55–69. DOI: https://doi.org/10.3126/ije.v8i2.25508

Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., Huybrechts, P., 2009. Evolution of supra-glacial lakes across the Greenland Ice Sheet. *Remote Sensing of Environment*, 113, 2164–2171. DOI: https://doi.org/10.1016/j.rse.2009.05.018

Wang, X., Shiyin, L., Haidong, H., Jian, W., Qiao, L., 2011.Thermal regime of a supraglacial lake on the debris-covered Koxkar Glacier, southwest Tianshan, China. *Environ. Earth Science*, 37, 175–183. DOI: https://doi.org/10.1007/s12665-011-1490-1

Wessels, R.L., Kargel, J.S., Kieffer, H.H., 2002. ASTER measurement of supraglacial lakes in the Mount Everest region of the Himalaya. *Annals of Glaciology*, 34, 399–408. DOI: https://doi.org/10.3189/172756402781817545

Wester, P., Misrhra, A., Mukherji, A., Shrestha, A.B. (Eds.). (2019). *The Hindu Kush Himalaya Assessment*. *The Hindu Kush Himalaya Assessment*. Springer International Publishing. DOI: https://doi.org/10.1007/978-3-319-92288-1