TEMPORAL ANALYSIS OF GLOFS IN HIGH-MOUNTAIN REGIONS OF ASIA AND ASSESSMENT OF THEIR CAUSES

KRISTÝNA FALÁTKOVÁ

Charles University, Faculty of Science, Department of Physical Geography and Geoecology, Czech Republic

ABSTRACT

Glacial lake outburst flood (or shortly GLOF) has become a well-known phenomenon, one of natural hazards occurring in glaciated high mountain areas of the world. The aim of this study was to investigate temporal distribution of these events in Asia and to assess causes of lake outbursts. Therefore, a search of scientific literature and reports was carried out resulting in 219 flood cases found. In order to detect possible differences in temporal distribution a group of ice-dammed lakes was detached and compared with the rest. Concerning spatial distribution of GLOFs, it is influenced by availability of scientific literature which is determined by research teams' region interest. Temporal analysis revealed a certain pattern in ice-dammed lake outburst distribution and notable difference between the two lake groups in terms of outburst occurrence within a year. The moraine-dammed lake outbursts were recorded earlier in an ablation season (compared to ice-dammed lakes) which could be attributed to different mechanism of dam failure. Majority of lake outburst causes were included in the category of dynamic causes (e.g. ice avalanche), long-term causes (e.g. dead-ice melting) were less represented. Results of the study imply there can be notable variations of temporal distribution and causes of GLOFs among individual mountain regions even within one continent. Therefore, varying behavior of potentially dangerous lakes should be taken into consideration when, for instance, proposing mitigation measures.

Keywords: GLOF, glacial lake, mountain region, temporal distribution, outburst cause

Received 3 February 2016; Accepted 13 June 2016

1. Introduction

Climate changes and its manifestations linked to mountain glaciation represent one of the most topical issues in the world of geosciences (Bates et al. 2008; Bliss et al. 2014; Li et al. 2007; Rowan et al. 2015; Zhao et al. 2015; Zhou et al. 2010). Faster rate of glacier melting leads to raised summer discharges in glacier-fed streams (Aizen et al. 2007; Wang et al. 2014), overfilling of glacial lake basins and destabilization of moraine dams. These processes may result in the phenomenon called GLOF (= glacial lake outburst flood), which has become a feared natural catastrophic process due to its difficult predictability, high velocity of spreading and often unexpectedly large affected area (Bajracharya and Mool 2009). The main goals of this paper are i) to analyze temporal distribution of recorded GLOFs, and ii) to assess causes of recorded glacial lakes outbursts.

The highest mountain range of the world, Himalayas, provide ideal conditions for the emergence of potential hazards of large proportions due to significant differences in elevations and very steep slopes, the term GLOF was developed for this area (Mool 1995). Climate change affects glaciers whose retreat or degradation results in the formation and development of potentially dangerous lakes (Chen et al. 2010; Komori 2008). These lakes can be of large dimensions and their outburst would cause a flood striking areas several tens to even hundreds of kilometers distant (Richardson and Reynolds 2000).

Other Asian mountain ranges where floods from glacial lake outbursts were recorded include Caucasus (Petrakov et al. 2007; Chernomorets et al. 2007), Pamir (Mergili et al. 2011), Hindu Kush-Karakoram (Gardelle et al. 2011) and Tien Shan (Narama et al. 2010; Janský et al. 2010).

2. Glacial lake outburst flood

Seasonal floods caused by snow melting or torrential rains have affected humans and their livelihood ever since. However, the GLOF, a natural hazard typical for post-LIA era, can be even more destructive – the highest recorded peak discharge was 30,000 $m^3 s^{-1}$ (Richardson and Reynolds 2000).

Recently, a rapid retreat of glaciers was recorded in Himalayas (Bolch et al. 2012; Chen et al. 2007) and other glaciated Asian mountain ranges (Sarikaya et al. 2012; Sorg et al. 2012; Shahgedanova et al. 2014) leading to a formation of new glacial lakes, enlarging of the existing ones and rising of a glacial lake outburst potential (Watanabe et al. 1994; Richardson and Reynolds 2000; Bajracharya and Mool 2009). These floods can reach extremely high flow rates and therefore are able to erode and transport huge amounts of material – up to millions m^3 (Hubbard et al. 2005). Consequently, debris flows reaching distances of as much as 200 km may evolve moving down a valley at higher speed than a flood wave due to double density

https://doi.org/10.14712/23361980.2016.12
Falátková, K. (2016):
Temporal analysis of GLOFs in high-mountain regions of Asia and assessment of their causes
AUC Geographica, 51, No. 2, pp. 145–154

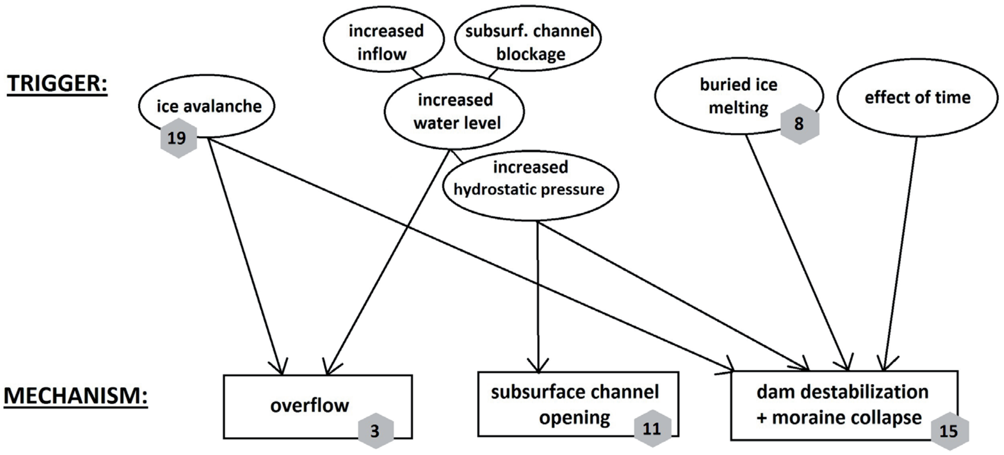

Fig. 1 Relationship of selected outburst triggers and mechanisms with number of cases.

compared to clear water (Richardson and Reynolds 2000). As GLOF is difficult to predict – outburst mechanism is very complex (Kershaw et al. 2005), longitudinal profile of mountain valleys is rather steep and there is often poor or non-existent warning system, material damage can be large and in some cases there could be even many casualties (Lliboutry et al. 1977).

It is important to understand the response of glaciers and glacial lakes to increase of air temperature, to identify potential risks and plan mitigation measures (Bajracharya and Mool 2009; Bennett and Glasser 2009). Remote sensing together with GIS models proved to be a vital tool in assessing risk and defining endangered areas (Bolch et al. 2011; Huggel et al. 2003; Komori 2008; Worni et al. 2012; Pitman et al. 2013).

Flood volume and course depends on many factors including the amount of water released from a lake, height, width and structure of its dam, outburst mechanism, valley shape and available quantity of sediment in the area affected by a flood (Costa and Schuster 1988). One example of an enormous lake outburst flood is an event from 1985, when part of a glacier terminus calved into Dig Tsho Lake, Nepal (Bajracharya and Mool 2009). A displacement wave ran over the dam which failed due to consequent erosion. Resulting flood wave had an initial flow rate of 2,000 $m^3 s^{-1}$ (Vuichard and Zimmermann 1987), Cenderelli and Wohl (2001) indicate even 2,350 $m^3 s^{-1}$. The consequences were noticeable even 90 km below the dam lake (Richardson and Reynolds 2000). Another catastrophic flood of 1994 from outburst of Luggye Tsho Lake was described by Richardson and Reynolds (2000), who claim that the flood wave (over 2 m high) was recorded on a hydrograph at distance greater than 200 kilometers from the source lake.

3. Methods

Total number of 219 cases of glacial lake outburst flood were compiled for this paper based on search of scientific publications and reports. The event parameters were searched as follows: lake's name, date of outburst (year, month, day), cause of outburst (probable trigger or mechanism), mountain range, and lake's coordinates. However, for some of the cases not all the desired information was available. In nine cases the exact year of event is not known, no information on cause of outburst was obtained in 17 cases, and the temporal analysis within a year was based on 128 cases only. The time span of compiled outburst floods begins in 1533 and ends with an event from 2012. Most recorded cases are from the 19th and 20th century, earlier ones are only sporadic.

When analyzing the GLOF cases a distinction is made between two groups – moraine-dammed lakes and ice-dammed lakes. Moraine-dammed lakes drain in most cases once, some do several times. Ice-dammed lakes, on the other hand, are dammed by a glacier blocking a valley; such lakes often form and drain repeatedly. The latter are set aside since the lake formation and consequent outburst are driven by different mechanism and glacier behavior (glacier retreat and degradation vs. glacier advance). And as the outburst is often repeated for decades, the statistics would be significantly influenced – 146 flood cases out of 219 were from ice-dammed lakes. Furthermore, the 146 cases were recorded within only a few localities: Inylchek glacier, Tien Shan (48), several valleys in upper Yarkant basin (24) and upper Indus basin (74), Hindu Kush-Karakoram. Spatial representation of the ice-dammed lake outburst floods is therefore rather unbalanced. The detachment of this group of cases allows to perform a comparative temporal distribution analysis between the two and to reveal differences in occurrence.

For 56 out of 73 cases of moraine-dammed lake outbursts there was information concerning GLOF cause. However, some sources stated an initial trigger of a lake outburst whereas the others mentioned an outburst mechanism. As there are more possible triggers leading to a certain outburst mechanism (Costa and Schuster

Tab. 1 Sources of information on GLOF cases.

		Number of cases with known					
Source	**No. of cases**	**Cause**	**Day**	**Month**	**Year**	**Time span**	**Mt range**
Gerasimov 1965	1	1	1	1	1	1963	Tien Shan
Gerassimow 1909	1	0	0	0	1	1909	Caucasus
Ives et al. 2010*	34	30	23	24	27	1935–2004	Himalayas
Liu et al. 2013	2	2	2	2	2	1998–2002	Himalayas
Liu et al. 2014	1	1	1	1	1	1988	Himalayas
Mergili et al. 2011	1	1	1	1	1	2002	Pamir
Narama et al. 2009	8	1	8	8	8	1970–1980	Tien Shan
Narama et al. 2010	7	5	6	6	7	1974–2008	Tien Shan
Petrakov et al. 2007	2	1	1	1	2	1993–2006	Caucasus
Petrakov et al. 2012	3	3	1	1	3	1988–2012	Tien Shan
Seinova and Zolotarev 2001	2	2	0	0	2	1958–1959	Caucasus
Wang et al. 2011	10	8	7	9	9	1955–2009	Himalayas
Yesenov and Degovets 1979	1	1	1	1	1	1977	Tien Shan
Glazirin 2010	48	48	37	48	48	1902–2005	Tien Shan
Hewitt and Liu 2010**	95	95	17	25	94	1533–2009	Karakoram
Iturrizaga 2005	3	3	0	0	3	1860–1909	Karakoram
Total	219	202	106	128	210		

* compiled from: Mool et al. 1995, 2001a, 2001b, Yamada 1998, Bajracharya et al. (2008); supplemented with information from: Wang et al. 2011

** supplemented with information from: Iturrizaga 2005

1988), some additional information would be necessary to assess the causes of all 56 events. In Figure 1 relationships of the identified triggers and mechanisms are specified.

Tha GLOF causes can be divided into long-term and dynamic causes according to Emmer and Cochachin (2013). The former include dam failures where an initial external dynamic trigger is absent, the latter are caused by a dynamic event (Yamada 1998).

4. Analysis of GLOFs

Following chapters assess the temporal distribution of outburst flood events and causes of lake outbursts within the high-mountain regions of Asia. Although the number of all outburst flood events is relatively high (219), not all enter the assessment as many lack some piece of information (Table 1).

Throughout the continent of Asia, information on a glacial lake outburst flood was found in following mountain ranges: Caucasus, Pamir, Tien Shan, Karakoram, and Himalayas. Altay and Central range of Kamchatka showed precondition for flood events as well, but no GLOF related publication from these regions was found in scientific literature.

Within Caucasus, information on only a few cases of outbursts were acquired (Petrakov et al. 2012), all of them situated in Elbrus region – surroundings of a glaciated massif of Mt. Elbrus (5,642 m asl). In Pamir, one case of lake outburst was recorded on the territory of Tajikistan (Mergili et al. 2011).

As many of Tien Shan ridges are glaciated, steep valleys and glacier retreat of last decades provide good conditions for lake outburst floods (Bolch 2007; Narama et al. 2010; Petrakov et al. 2012; Yerokhin 2003). However, probably only a minor number of cases were described in scientific literature as this region has long been rather neglected by foreign researchers. Repeatedly drained Lake Merzbacher, dammed by a glacier Inylchek, is an exception as it has been monitored closely for more than a century (Glazirin 2010).

Within the Hindu Kush-Karakoram range, only cases of ice-dammed lake outburst were found (Hewitt and Liu 2010; Iturrizaga 2005). These lakes are situated in upper parts of two basins: Indus and Yarkant, and floods caused by sudden drainage of these lakes have been regularly recorded by local population of downstream villages since 1830s.

A large number of glacial lake outburst floods were recorded in the Himalayas, partly because of the extensiveness of this mountain system and therefore vast glaciated area, but also due to the considerable interest of research teams from all around the world (Benn et al. 2012; Bolch and Kamp 2006; Rana et al. 2000; Richardson and Reynolds 2000; Quincey et al. 2007; Yamada and Sharma 1993). Number of potentially dangerous lakes and GLOFs has been rising in Himalayas since 1930 (Liu

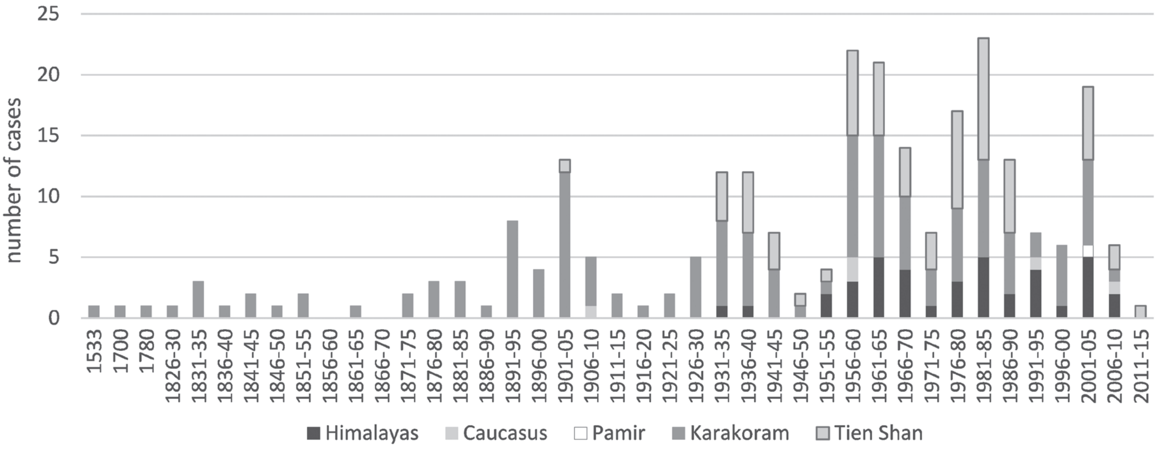

Fig. 2 Temporal distribution of GLOFs according to a mountain range.

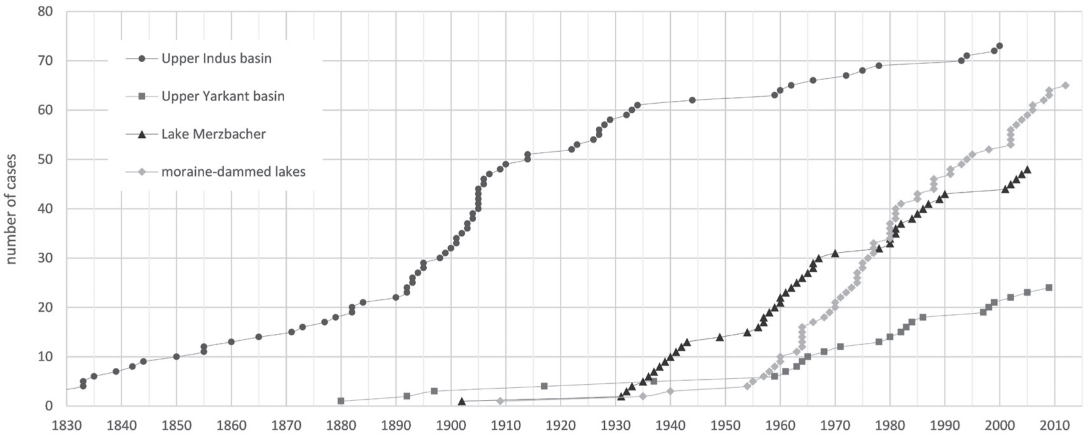

Fig. 3 Cumulative number of GLOFs in Asia divided into 4 categories.

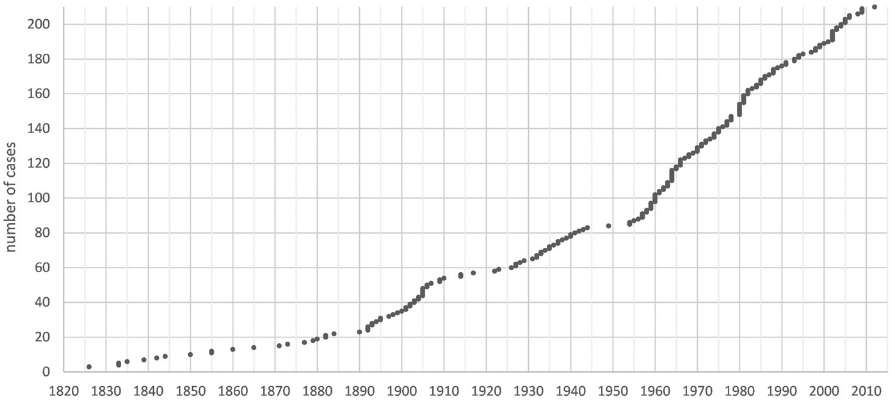

Fig. 4 Cumulative number of all GLOFs in high mountain Asia.

et al. 2013; Bolch et al. 2008), Richardson and Reynolds (2000) report that 33 outburst floods have taken place here until 2000.

4.1 GLOF temporal distribution

Outburst flood events with known year (210 cases) were compiled according to a mountain range where they occurred and classified into five-year segments (Figure 2). Number of recorded cases begins to rise at the end of the 19th century and peaks between 1901 and 1905 when 13 GLOFs occurred. This is followed by a noticeable drop in numbers around 1920. Similar pattern continues further on (peak in the 1930s and drop around the year 1950) with overall higher number of cases since late 1950s. Last significant drop in number of flood cases emerges in 1990s with the average of 1.3 cases per year in all Asian mountain ranges together, which is rather low compared to previous decade (1980s: 2.8 cases/year).

Comparison of the regions in terms of temporal distribution of cases is focused on three ranges with higher number of GLOFs – Himalayas, Karakoram, and Tien Shan. There is consistency among the ranges around the year 1950 when only very few cases occurred. However, the second drop in 1990s is not significant for either Himalayas or Karakoram whereas in Tien Shan not a single outburst flood was recorded. On the other hand, the periods with high numbers of cases are mostly coincident in all three mountain ranges.

An interesting pattern emerges when plotting the data into cumulative number of cases (Figure 3). The data were divided into groups of moraine-dammed lakes and ice-dammed lakes, the latter was further divided by watershed into three parts (Upper Indus basin, Upper Yarkant basin, Lake Merzbacher). All the localities where floods from ice-dammed lakes were recorded show perceptible grouping of cases, so that periods with high and very low number of cases alternate.

In the Indus basin (predominantly in valleys of Shyok, Shimshal, and Hunza) floods were recorded rather regularly during most of the 19th century. However, the first decade od the 20th century was characterized by significantly increased frequency of GLOFs; on average 1.7 cases per year occurred in the region. In contrast, the following period had only two outburst cases between the 1910 and 1922 events. Similar but less pronounced steps follow with rarely any cases recorded in periods 1935–1959 and 1978–1994.

GLOFs in the Yarkant basin also exhibit such pattern – rather short periods of higher and low number of cases alternate. Although the pattern emerged only since 1960s, it seems to be rather regular as well as pattern of outburst cases of Lake Merzbacher. The lake dammed by glacier Inylchek shows periods of almost annual drainage followed by shorter periods with one or no case.

The curve representing cumulative number of moraine-dammed lake events does not exhibit such obvious pattern, although certain periods of lower and higher outburst flood numbers can be found. However, it is not in accordance with the ice-dammed lake cases, except for the time around 1980 when many cases were recorded. That is also apparent in Figure 4 which shows development of cumulative number of all GLOFs in Asia. The blotting effect of moraine-dammed lake cases on the described pattern is confirmed as the alternating periods are visible only until the 1950s when the moraine-dammed GLOFs became frequent.

Distribution of GLOFs within a year was analyzed based on 128 cases with known month of occurrence. The floods are distributed mainly among months characteristic of ablation (June–September), however, there are even few cases which occurred in unusual time of a year (Figure 5). As expected, most outbursts were recorded in August, less in July and September. Slight difference arises due to separation of ice-dammed and moraine-dammed lakes: the former having most cases later in a year (1. August 2. September 3. October) compared to the latter (1. July 2. August 3. June).

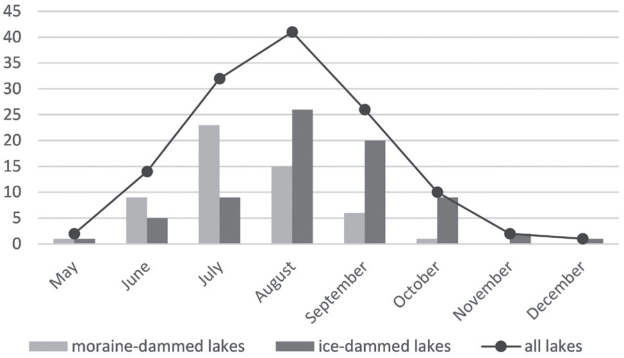

Fig. 5 Monthly distribution of GLOFs with distinction between moraine-dammed and ice-dammed lakes.

4.2 GLOF causes

The cause of GLOF may be difficult to determine as witness is rarely present and evidence may not always indicate to a particular cause with certainty. A total of 202 cases out of 219 were appointed with a cause of a flood, although not all were specific in terms of the outburst trigger.

All ice-dammed lake outbursts, i.e. 72.1% of all cases, were set aside into a category of increased hydrostatic pressure (Zhang 1992). Hewitt and Liu (2010) and Glazirin (2010) describe the mechanism of release of water detained behind the glacier tongue as a consequence of raised hydrostatic pressure which led to partial glacier uplift and opening of drainage channels.

Concerning causes of moraine-dammed lake outbursts, there are only 38 cases with known trigger, 18 with known outburst mechanism, and 17 cases without any information (Figure 6). The most often mentioned cause of lake outburst was ice avalanche falling into a lake (34%). Fall of mass into a lake generates a displacement wave which may either overflow the dam and commence its incision or destabilize the dam and lead to its collapse (Clague and Evans 2000).

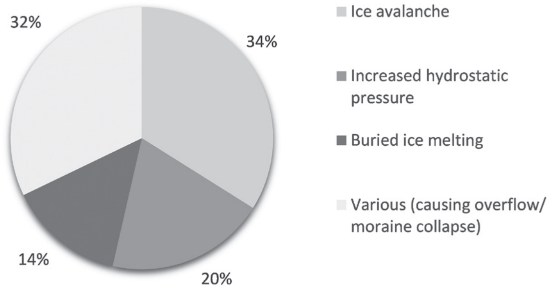

Fig. 6 A percentage share of triggers of floods from moraine-dammed lakes in Asia.

In case a lake does not have a surface outflow, it is sensitive to the amount of inflowing water. Significantly increased inflow (either from rapid snow melt or heavy

Tab. 2 Causes of lake outburst floods according to mountain ranges.

Cause / **Mt range**	**Moraine dam**				**Ice dam**	**Total**
	Ice avalanche	**Increased hydrostatic pressure**	**Buried ice melting**	**Various (*resulting in overflow / moraine collapse*)**	**Increased hydrostatic pressure**	
Himalayas	19	/	6	16	/	41
Tien Shan	/	8	1	2	48	59
Caucasus	/	2	1	/	/	3
Pamir	/	1	/	/	/	1
Karakoram	/	/	/	/	97	97
Total	19	11	8	18	145	201

rainfall) causes lake water level to rise together with hydrostatic pressure on a dam. This may lead to subsurface channel opening and lake drainage, which happened in 20% of the cases.

The third specifically mentioned outburst cause was melting of buried ice (14%), which is a part of a moraine damming a lake. The ice melting may disrupt the dam structure and destabilize it to such extent, that it cannot withstand the hydrostatic pressure of detained water and it collapses (Yamada 1998). A moraine dam degraded due to buried ice melting is also more prone to collapse even with a minor trigger (Clague and Evans 2000).

Remaining cases with known mechanism of outburst (32%) could not be classified to causes as both "overflow" and "moraine collapse" are too general and may be a consequence of various triggers.

Based on the knowledge of moraine-dammed lake outburst causes, these can be further divided into long-term and dynamic causes. Ice avalanche belongs among dynamic causes, increased hydrostatic pressure and cases with overflow as an outburst mechanism were also incorporated in this group. The long-term causes include buried ice melting. The ratio of dynamic and long-term causes then makes 33 : 8, with further 15 cases unclassified. The cause of ice-dammed lakes outburst (increased hydrostatic pressure) is considered also dynamic, which means that dynamic causes of lake outburst floods are generally more frequent in Asian high mountain areas.

Deployment of GLOF events in Asia together with the cause of lake outburst are summarized in Table 2. Although there are not enough cases for all the mountain ranges, some interesting differences in terms of outburst causes arise among them. Ice avalanche appears as a relatively common cause of outburst in Himalayas, however, avalanche or other mass movement into a lake was not recorded as a lake outburst cause anywhere else. In Tien Shan, Caucasus and Pamir the lakes drained often by opening of subsurface channels due to incresed hydrostatic pressure whereas in Himalayas this cause did not occur.

5. Discussion

Some of the major glacial lake outburst floods on the territory of Asia were studied in detail, e.g. Luggye Tsho in Bhutan Himalaya (Watanabe and Rothacher 1996), Tam Pokhari in Mt. Everest region (Osti and Egashira 2009) or Lake Zyndan in Tien Shan (Narama et al. 2010). Studies encompassing more lake outbursts include Bajracharya et al. (2008), Narama et al. (2009), Hewitt and Liu (2010), ICIMOD (2011), or Chen et al. (2010). This paper attempted to compile data on all recorded outburst floods in Asia, however, the main obstacle became unbalanced availability of GLOF reports among the mountain regions. Since most cases of GLOF included in this analysis were found in only a few articles dealing with specific locations or time periods, all statistics can be slightly biased due to the uneven spatial (and temporal) distribution of the obtained data. Special case is a group of ice-dammed lakes that are located within few sites and their outbursts are repeated. Although statistics from these data cannot be generalized, they provide interesting insight into the temporal distribution of the outburst floods and a comparison with outbursts from glacial lakes.

Concerning the temporal distribution, a significantly lower number of cases was recorded in 1950s and 1990s, on the contrary, 1960s were a period of very high number of cases. Chen et al. (2010) argue that lake outbursts are closely related to positive anomalous air temperature of a year. Precipitation, Chen et al. (2010) add, plays a role in flood peak discharge value. A certain correspondence was found for Tien Shan as both air temperature and precipitation in 1950s were at their low compared to previous and following decade, in the 1990s the air temperature raised rather slowly from its low at the end of previous decade (Černý et al. 2007). Liu et al. (2014) studied correlation between GLOF events and air temperature in Tibet and confirm that 1960s, 1980s and 2000s were very active periods for GLOFs due to higher temperatures during ablation season but also during accumulation.

Analysis of events distribution within a year found a noticeable difference between the ice- and moraine-dammed lakes with the latter draining earlier in a year. Ice-dammed lakes may react with greater delay as glacier dam uplift requires large amount of water causing sufficiently increased hydrostatic pressure (Glazirin 2010). However, Huss et al. (2007) and Glazirin (2010) both indicate a shift of ice-dammed lakes drainage to earlier time within a year mainly in the second half of the 20th century. It means the diference between the two lake types would not probably be that large if only the latest data were included. Liu et al. (2014) also note that the timing of outburst is influenced by lake's altitude – the higher altitude, the later burst within a season. However, in our case the lake's altitude is not of such importance to influence the outburst timing as the lakes are situated in similar altitude. The drained moraine-dammed lakes lay between 2,500 m and 5,500 m asl. and the ice-dammed ones in an altitude probably between 3,000–4,300 m asl. (the presize location within a valley – the damming glacier – is often unknown).

While frequency of ice-dammed lake outbursts has been significantly lowered since 1930 in Upper Indus basin (Hewitt and Liu 2010), it seems that floods from moraine-dammed lakes began to occur much more often since 1950s. As Hewitt (1982) mentions, it could be associated with general glacier recession which may have opposite effect on the observed lake groups. The overall higher numbers of moraine-dammed lake outbursts could be contributed to both accelerated glacier retreat as well as increased interest of researchers or better accessibility of the records by internet searching (Bajracharya et al. 2007).

Assessment of floods in terms of outburst causes is limited by the fact that some authors reported an outburst mechanism, not a trigger, and so the cause was specified for 38 cases of floods from a moraine-dammed lake. However, conclusions of this paper are relatively in accordance with other GLOF-related studies. Narama et al. (2009) reported buried ice melting and moraine collapse due to headwater erosion of the dam and increased inflow leading to subsurface channel opening as main causes of lake outbursts in northern Tien Shan. Most frequent causes of GLOFs in Tibet are, according to Liu et al. (2013), overflow due to fall of ice into a lake and moraine deformation and collapse due to piping, very similar results are also presented by Emmer and Cochachin (2013).

6. Conclusions

Cases of floods from glacial lake outburst, known by the acronym GLOF, were searched within the territory of Asia. Alpine glaciated areas around the world face this threat mainly due to retreat of glaciers and the subsequent formation of lakes or glacier dynamics generally. Within Asia, cases of flood from moraine-dammed lakes were found in following mountain regions: Caucasus, Pamir, Tien Shan and Himalaya. A large number of floods from lakes dammed by a glacier tongue were recorded in the Hindu Kush-Karakoram mountain range.

Spatial distribution of GLOF cases used in this paper is rather unbalanced. It is probably influenced by availability of reports and publications and the fact that some areas are more favorable for foreign researchers than others. Regarding temporal distribution of found outburst events, significant increase is apparent since 1950s, earlier cases include mostly ice-dammed lake outbursts. Generally, certain periods of higher (1960s, 1980s) and lower (1990s) number of events arise, this pattern is even more obvious for ice-dammed lake cases. Most outbursts occurred within ablation season with peak in August which is consistent with general assumptions. Slight difference was observed between moraine- and ice-dammed lakes as the former tend to drain earlier in a year.

Concerning causes of lake outburst, increased hydrostatic pressure leading to englacial channel opening was appointed to all ice-dammed lake cases (145). The most common cause of moraine-dammed lake outburst is an ice avalanche falling into a lake. Other observed causes include melting of buried ice and increased hydrostatic pressure on a dam due to water level rise. Although the proportion of outburst causes differ among the mountain ranges, dynamic causes constitute the majority of cases.

The main contribution of this paper is an assembly and following comparison of all available GLOFs in high mountain regions of Asia. Unlike other studies, it encompasses both moraine-dammed and glacier-dammed lakes and focuses on differences between the two groups uncovered by temporal analysis of outburst occurrence. Found patterns characterised by alternating periods of high and low number of events could be further analyzed in relation to climate in order to improve our knowledge on link between GLOFs and climatic elements. This is, however, beyond the scope of this paper.

Acknowledgements

Author would like to thank Doc. V. Vilímek and two anonymous reviewers for their comments and recommendations.

REFERENCES

AIZEN, V. B., AIZEN, E. M., KUZMICHENOK, V. A. (2007). Glaciers and hydrological changes in the Tien Shan: simulation and prediction. Environmental Research Letters, 2(4), 1–10. http://dx.doi.org/10.1088/1748-9326/2/4/045019

BAJRACHARYA, S. R., MOOL, P. (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. Annals of Glaciology, 50(53), 81–86. http://dx.doi.org/10.3189/172756410790595895

BAJRACHARYA, S. R., MOOL, P. K., SHRESTHA, B. R. (2007). Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan. Kathmandu: International Centre for Integrated Mountain Development.

BAJRACHARYA, S. R., MOOL, P. K., SHRESTHA, B. R. (2008). Global climate change and melting of Himalayan glaciers. Melting glaciers and rising sea levels: Impacts and implications, 28–46.

BATES, B. C., KUNDZEWICS, Z. W., WU, S., PALUTIKOF, J. P. (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

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. http://dx.doi.org/10.1016/j.earscirev.2012.03.008

BENNETT, M. R., GLASSER, N. F. (2009). Glacial geology: ice sheets and landforms. 2nd edition. Chcichester: Wiley-Blackwell, 385 pp.

BLISS, A., HOCK, R., RADIĆ, V. (2014). Global response of glacier runoff to twenty-first century climate change. Journal of Geophysical Research: Earth Surface, 119(4), 717–730. http://dx.doi.org/10.1002/2013jf002931

BOLCH, T. (2007). Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Global and Planetary Change, 56(1), 1–12. http://dx.doi.org/10.1016/j.gloplacha.2006.07.009

BOLCH, T., BUCHROITHNER, M. F., PETERS, J., BAESSLER, M., BAJRACHARYA, S. (2008). Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. Natural Hazards and Earth System Science, 8(6), 1329–1340. http://dx.doi.org/10.5194/nhess-8-1329-2008

BOLCH, T., KAMP, U. (2006). Glacier mapping in high mountains using DEMs, Landsat and ASTER data. Grazer Schriften der Geographie und Raumforschung, 41, 37–48.

BOLCH, T., KULKARNI, A., KÄÄB, A., HUGGEL, C., PAUL, F., COGLEY, J. G., FREY, H., KARGEL, J. S., FUJITA, K., SCHEEL, M., BAJRACHARYA, S., STOFFEL, M. (2012). The state and fate of Himalayan glaciers. Science, 336(6079), 310–314. http://dx.doi.org/10.1126/science.1215828

BOLCH, T., PETERS, J., YEGOROV, A., PRADHAN, B., BUCHROITHNER, M., BLAGOVESHCHENSKY, V. (2011). Identification of potentially dangerous glacial lakes in the nothern Tien Shan. Natural Hazards, 59, 1691–1714. http://dx.doi.org/10.1007/s11069-011-9860-2

CENDERELLI, D. A., WOHL, E.E. (2001). Peak discharge estimates of glacial-lake outburst floods and 'normal' climatic floods in the Mount Everest region, Nepal. Geomorphology, 40(1–2), 57–90. http://dx.doi.org/10.1016/S0169-555X(01)00037-X

ČERNÝ, M., JANSKÝ, B., ŠOBR, M., ENGEL, Z., ČESÁK, J., KOCUM, J., ŽÁČEK, M., YEROKHIN, S. A. Monitoring of high mountain glacial lakes and protection of population against catastrophic impacts of floods caused by moraine lake outbursts. Final report of Development Cooperation Project between Czech and Kyrgyz republic. RP/27/2004, 2007, GEOMIN družstvo, Jihlava, 206 pp.

CHEN, X., CUI, P., LI, Y., YANG, Z., QI, Y. (2007). Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet). Geomorphology, 88(3–4), 298–311. http://dx.doi.org/10.1016/j.geomorph.2006.11.012

CHEN, Yaning, XU, C., CHEN, Yapeng, LI, W., LIU, J. (2010). Response of glacial-lake outburst floods to climate change in the Yarkant River basin on northern slope of Karakoram Mountains, China. Quaternary International, 226(1–2), 75–81. http://dx.doi.org/10.1016/j.quaint.2010.01.003

CHERNOMORETS, S. S., PETRAKOV, D. A., KRYLENKO, I. V., KRYLENKO, I. N., TUTUBALINA, O. V., ALEJNIKOV, A. A., TARBEEVA, A. M. (2007). Dynamics of glacial-lake complex Bashkara and evaluation of debris flow formation risk in Adyl-Su valley (Caucasus). Криосфера Земли, 11(1), 72–84. (in Russian)

CLAGUE, J. J., EVANS, S.G. (2000). A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews, 19, 1763–1783. http://dx.doi.org/10.1016/S0277-3791(00)00090-1

COSTA, J. E., SCHUSTER, R. L. (1988). The formation and failure of natural dams. Geological Society of America Bulletin, 100, 1054–1068. http://dx.doi.org/10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2

EMMER, A., COCHACHIN, A. (2013): The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera, and Himalayas. AUC Geographica, 48(2), 5–15. http://dx.doi.org/10.14712/23361980.2014.23

GARDELLE, J., ARNAUD, Y., BERTHIER, E. (2011). Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Global and Planetary Change, 75(1–2), 47–55. http://dx.doi.org/10.1016/j.gloplacha.2010.10.003

GERASSIMOW, A. P. (1909). O proryve lednikovogo ozera na NO sklone Elbrusa [About glacial lake outburst at the north-east slope of Mt. Elbrus]. Izvestiya Geolkoma, 28(7), 156–160. (in Russian)

GERASIMOV, V.A. (1965). Issykskaia katastrofa 1963 g. i otrazhenie ee in geomorfoogii doliny r. Issyk [The Issyk catastrophe in 1963 and its effect on geomorphology of the Issyk River valley]. Akademiia Nauk SSSR, Izvestiia Vsesoiuznogo, Geograficheskogo Obshchestva, 97(6), 541–547. (in Russian)

GLAZIRIN, G. E. (2010). A century of investigations on outbursts of the ice-dammed Lake Merzbacher (Central Tien Shan). Austrian Journal of Earth Sciences, 103(2), 171–179.

HEWITT, K. (1982). Natural dams and outburst floods of the Karakoram Himalaya. In Hydrological Aspects of Alpine and High Mountain Areas (Proceedings of the Exeter Symposium, July 1982), 259–269.

HEWITT, K., LIU, J. (2010). Ice-dammed lakes and outburst floods, Karakoram Himalaya: historical perspectives on emerging threats. Physical Geography, 31(6), 528–551. http://dx.doi.org/10.2747/0272-3646.31.6.528

HUBBARD, B., HEALD, A., REYNOLDS, J. M., QUINCEY, D., RICHARDSON, S. D., ZAPATA, M. L., SANTILLAN, N. P., HAMBREY, M. J. (2005). Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru. Earth Surface Processes and Landforms, 30, 1251–1264. http://dx.doi.org/10.1002/esp.1198

HUGGEL, C., KÄÄB, A., HAEBERLI, W., KRUMMENACHER, B. (2003). Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Natural Hazards and Earth System Science, 3(6), 647–662. http://dx.doi.org/10.5194/nhess-3-647-2003

HUSS, M., BAUDER, A., WERDER, M., FUNK, M., HOCK, R. (2007). Glacier-dammed lake outburst events of Gornersee, Switzerland. Journal of Glaciology, 53 (181), 189–200. http://dx.doi.org/10.3189/172756507782202784

ICIMOD (2011). Glacial lakes and glacial lake outburst floods in Nepal. International Centre for Integrated Mountain Development, Kathmandu: ICIMOD, 99 pp.

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. http://dx.doi.org/10.1016/j.jseaes.2004.04.011

IVES, J. D., SHRESTHA, R. B., MOOL, P. K. (2010). Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment. Kathmandu: ICIMOD.

JANSKÝ, B., ŠOBR, M., ENGEL, Z. (2010). Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan. Limnologica, 40, 358–364. http://dx.doi.org/10.1016/j.limno.2009.11.013

KERSHAW, J. A., CLAGUE, J. J., EVANS, S. G. (2005). Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada. Earth Surface Processes and Landforms, 30, 1–25. http://dx.doi.org/10.1002/esp.1122

KOMORI, J. (2008). Recent expansions of glacial lakes in the Bhutan Himalayas. Quaternary International, 184, 177–186. http://dx.doi.org/10.1016/j.quaint.2007.09.012

LI, Z. Q., SHEN, Y. P., WANG, F. T., LI, H. L., DONG, Z. W., WANG, W. B., & WANG, L. (2007). Response of glacier melting to climate change-take Urumqi Glacier No. 1 as an example. Journal of Glaciology and Geocryology, 3.

LIU, J., TANG, C., CHENG, Z. (2013). The Two Main Mechanisms of Glacier Lake Outburst Flood in Tibet, China. Journal of Mountain Science, 10(2), 239–248. http://dx.doi.org/10.1007/s11629-013-2517-8

LIU, J. J., CHENG, Z. L., SU, P. C. (2014). The relationship between air temperature fluctuation and Glacial Lake Outburst Floods in Tibet, China. Quaternary International, 321, 78–87. http://dx.doi.org/10.1016/j.quaint.2013.11.023

LLIBOUTRY, I., MORALES, B., PAUTRE, A., SCHNEIDER, B. (1977). Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I: Historical failure of morainic dams, their causes and prevention. Journal of Glaciology, 18, 239–254.

MERGILI, M., SCHNEIDER, J. F. (2011). Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Natural Hazrads and Earth System Sciences, 11, 1447–1462. http://dx.doi.org/10.5194/nhess-11-1447-2011

MERGILI, M., SCHNEIDER, D., WORNI, R., SCHNEIDER, J. (2011). Glacial lake outburst floods in the Pamir of Tajikistan: challenges in prediction and modelling. In 5th international conference on debris-flow hazards mitigation: mechanics, prediction and assessment, University of Padova, Italy, pp. 14–17.

MOOL, P. K. (1995). Glacier lake outburst flood in Nepal. Journal of Nepal Geological Society, 11, 273–280.

MOOL, P. K., BAJRACHARYA, S. R., JOSHI, S. P. (2001a). Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan regions – Nepal. Kathmandu: ICIMOD.

MOOL, P. K., WANGDA, D., BAJRACHARYA, S. R., KUNZANG, K., GURUNG, D. R., JOSHI, S. P. (2001b). Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan region – Bhutan. Kathmandu: ICIMOD.

NARAMA, C., DUISHONAKUNOV, M., KÄÄB, A., DAIYROV, M., ABDRAKHMATOV, K. (2010). The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan. Natural Hazards and Earth System Sciences, 10, 647–659. http://dx.doi.org/10.5194/nhess-10-647-2010

NARAMA, C., SEVERSKIY, I., YEGOROV, A. (2009). Current State of Glacier Changes, Glacial Lakes, and Outburst Floods in the Ile Ala-Tau and Kungöy Ala-Too Ranges, Northern Tien Shan Mountains. Geographical Studies, 84(1), 22–32. http://dx.doi.org/10.7886/hgs.84.22

OSTI, R., EGASHIRA, S. (2009). Hydrodynamic characteristics of the Tam Pokhari Glacial Lake outburst flood in the Mt. Everest region, Nepal. Hydrological Processes, 23(20), 2943–2955. http://dx.doi.org/10.1002/hyp.7405

PETRAKOV, D. A., KRYLENKO, I. V., CHERNOMORETS, S. S., TUTUBALINA, O. V., KRYLENKO, I. N., SHAKHMINA, M. S. (2007). Debris flow hazard of glacial lakes in the Central Caucasus. In Chen, Y., Major, S. (eds.). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Netherlands: Millpress, 703–714.

PETRAKOV, D.A., TUTUBALINA, O.V., ALEINIKOV, A.A., CHERNOMORETS, S.S., EVANS, S.G., KIDYAEVA, V.M., KRYLENKO, I.N., NORIN, S.V., SHAKHMINA, M.S., SEYNOVA, I.B. (2012). Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst. Natural Hazards, 61(3), 1293–1316. http://dx.doi.org/10.1007/s11069-011-9983-5

PITMAN, E.B., PATRA, A.K., KUMAR, D., NISHIMURA, K., KOMORI, J. (2013). Two phase simulations of glacier lake outburst flows. Journal of Computational Science, 4, 71–79. http://dx.doi.org/10.1016/j.jocs.2012.04.007

QUINCEY, D. J., RICHARDSON, S., LUCKMAN, A., LUCAS, R., REYNOLDS, J., HAMBREY, M., GLASSER, N.F. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Global and Planetary Change, 56, 137–152. http://dx.doi.org/10.1016/j.gloplacha.2006.07.013

RANA, B., SHRESTHA, A. B., REYNOLDS, J. M., ARYAL, R. (2000). Hazard assessment of the Tsho Rolpa Glacier Lake and ongoing. Journal of Nepal Geological Society, 22, 563–570.

RICHARDSON, S. D., REYNOLDS, J. M. (2000). An overview on glacial hazards in the Himalayas. Quaternary International, 65–66, 31–47. http://dx.doi.org/10.1016/S1040-6182(99)00035-X

ROWAN, A. V., EGHOLM, D. L., QUINCEY, D. J., GLASSER, N. F. (2015). Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. Earth and Planetary Science Letters, 430, 427–438. http://dx.doi.org/10.1016/j.epsl.2015.09.004

SARIKAYA, M. A., BISHOP, M. P., SHRODER, J. F., OLSENHOLLER, J. A. (2012). Space-based observations of Eastern Hindu Kush glaciers between 1976 and 2007, Afghanistan and Pakistan. Remote Sensing Letters, 3(1), 77–84. http://dx.doi.org/10.1080/01431161.2010.536181

SEINOVA, I. B., ZOLOTAREV, E. A. (2001). Glaciers and debris flows in the Elbrus region (evolution of glaciation and debris flow activity). Nauchny Mir, Moscow. (in Russian)

SHAHGEDANOVA, M., NOSENKO, G., KUTUZOV, S., ROTOTAEVA, O., KHROMOVA, T. (2014). Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st century observed with ASTER satellite imagery and aerial photography. The Cryosphere, 8(6), 2367–2379. http://dx.doi.org/10.5194/tc-8-2367-2014

SORG, A., BOLCH, T., STOFFEL, M., SOLOMINA, O., BENISTON, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Climate Change, 2(10), 725–731. http://dx.doi.org/10.1038/nclimate1592

VUICHARD, D., ZIMMERMANN, M. (1987). The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences. Mountain Research and Development, 91–110. http://dx.doi.org/10.2307/3673305

WANG, G., TANDING, Y., YANG, G., XIAOXIN, Y., DAMBARU, B. K. (2011) A First-order Method to Identify Potentially Dangerous Glacial Lakes in a Region of the Southeastern Tibetan Plateau. Mountain Research and Development, vol. 31, no. 2, pp. 122–130. http://dx.doi.org/10.1659/MRD-JOURNAL-D-10-00059.1

WANG, S., ZHANG, M., PEPIN, N. C., LI, Z., SUN, M., HUANG, X., WANG, Q. (2014). Recent changes in freezing level heights in High Asia and their impact on glacier changes. Journal of Geophysical Research: Atmospheres, 119(4), 1753–1765. http://dx.doi.org/10.1002/2013jd020490

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, 14(4), 329–340. http://dx.doi.org/10.2307/3673729

WATANABE, T., ROTHACHER, D. (1996). The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya. Mountain Research and Development, 16(1), 77–81. http://dx.doi.org/10.2307/3673897

WORNI, R., STOFFEL, M., HUGGEL, C., VOLZ, C., CASTELLER, A., LUCKMAN, B. (2012). Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). Journal of Hydrology, 444–445, 134–145. http://dx.doi.org/10.1016/j.jhydrol.2012.04.013

YAMADA, T. (1998). Glacier lake and its outburst flood in the Nepal Himalaya. Tokyo, Japanese Society of Snow and Ice. Data Center for Glacier Research.

YAMADA, T., SHARMA, C.K. (1993). Glacier Lakes and Outburst Floods in the Nepal Himalaya. Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992). IAHS Publ. no. 218, 319–330.

YEROKHIN, S. A. (2003). Study and monitoring of dam failure safety of high-mountain lakes in Kyrgyzstan. State Institute of Geology, Bishkek, 156 pp.

YESENOV, U. Y., DEGOVETS, A. S. (1979). Catastrophic mudflow on the Bol'shaya Almatinka River in 1977. Soviet Hydrology: Selected Papers, 18(2), 158–160.

ZHANG, X. S. (1992) Investigation of glacier bursts of the Yarkant River in Xinjiang, China. Annals of Glaciology, 16, 135–139.

ZHAO, Q., ZHANG, S., DING, Y. J., WANG, J., HAN, H., XU, J., ZHAO, C., GUO, W., SHANGGUAN, D. (2015). Modeling Hydrologic Response to Climate Change and Shrinking Glaciers in the Highly Glacierized Kunma Like River Catchment, Central Tian Shan. Journal of Hydrometeorology, 16(6), 2383–2402. http://dx.doi.org/10.1175/JHM-D-14-0231.1

ZHOU, S., KANG, S., GAO, T., ZHANG, G. (2010). Response of Zhadang Glacier runoff in Nam Co Basin, Tibet, to changes in air temperature and precipitation form. Chinese Science Bulletin, 55(20), 2103–2110. http://dx.doi.org/10.1007/s11434-010-3290-5

RESUMÉ

Časová analýza GLOF událostí ve vysokohorských oblastech Asie a zhodnocení jejich příčin

Práce se zabývá výskytem povodní způsobených vyprázdněním ledovcového jezera ve vysokohorských oblastech Asie a příčinami selhání hráze. V odborné literatuře byly vyhledány informace o tomto typu povodní v následujících horských masivech: Kavkaz, Pamír, Ťan Šan, Karákoram a Himálaj. Celkem bylo nalezeno 219 případů povodní z ledovcových jezer, z toho 145 případů u jezer hrazených ledovcem, ostatní hrazené morénou či nacházející se na morénovém valu. Co se časové distribuce týče, byla zjištěna období s nižším a vyšším výskytem průvalů ledovcových jezer, nejmarkantněji se to projevilo u jezer hrazených ledovcem. Drobné rozdíly mezi oběma skupinami jezer se vyskytly při analýze distribuce událostí v rámci roku. Většina povodní se vyskytla během ablační sezóny, ty způsobené vyprázdněním jezer hrazených ledovcem však byly zaznamenány spíše později (srpen–říjen) oproti povodním z morénových jezer (červen–srpen). Příčina vyprázdnění jezera byla zjištěna celkem pro 202 událostí, velká část z nich však nebyla dostatečně specifická. Mimo zvýšení úrovně hladiny a tím i zvýšení hydrostatického tlaku, jež vede k otevření podpovrchových odtokových kanálů, byla nejčastější příčinou ledová lavina zaznamenána pouze u případů z Himálaje. Další zjištěnou příčinou bylo tání pohřbeného ledu v hrázi.

Kristýna Falátková
Charles University, Faculty of Science
Department of Physical Geography and Geoecology
Albertov 6, 128 43 Prague 2
Czech Republic
E-mail: falatkok@natur.cuni.cz