Limits and challenges to compiling and developing a database of glacial lake outburst floods

A. Emmer, V. Vilímek, C. Huggel, J. Klimeš & Y. Schaub

Landslides
Journal of the International Consortium on Landslides

ISSN 1612-510X
Volume 13
Number 6

Landslides (2016) 13:1579-1584
DOI 10.1007/s10346-016-0686-6

Springer

Landslides (2016) 13:1579–1584
DOI 10.1007/s10346-016-0686-6
Received: 18 November 2015
Accepted: 8 February 2016
Published online: 17 February 2016

A. Emmer · V. Vilímek · C. Huggel · J. Klimeš · Y. Schaub

Limits and challenges to compiling and developing a database of glacial lake outburst floods

Abstract A unified database of glacial lake outburst floods (GLOFs) has been created for analysis and future natural hazard evaluations. The data from individual case studies fill the database at a primary level, while the regional and global scales are more suitable for evaluating the information. There is enhanced research activity in this topic worldwide due to ongoing environmental changes, and this is apparent in the database. Database compilation is linked to the International Programme on Landslides (IPL) because different types of slope movements are the most common triggering factors for glacial lake outburst floods, and the outburst floods, on the other hand, often initiate different types of slope movements.

Keywords Glacial lake outburst floods · GLOF · Database · ICL/IPL activities · Natural hazards

Introduction

The International Programme on Landslides (IPL) Project No. 179 (www.iplhq.org) entitled "Database of glacial lake outburst floods (GLOFs)" began in 2013. Its objective is to create a readily accessible database of glacial lake outburst floods (GLOFs; glofs-database.org) that have occurred across the globe since the Little Ice Age by collecting and unifying data about these events from various sources. The original duration of the project was until the end of 2015, with future continuation expected. In the first stage (Vilímek et al. 2014), we introduced the structure of the database, collaborating partners, data sources and methodology, and preliminary results describing regional differences in GLOF occurrences. The objective of this report is to describe the current state of the database and discuss limits and challenges met during its compilation and development.

Even though the webpage of the GLOF database is still in its early stages of filling, the project has received positive feedback from the scientific community (in terms of data requests and offers) and has also served as a platform for collaboration between scientific institutions in different parts of the world. The database falls into the framework of the strategy of the IPL (e.g., Sassa 2012) and is one of the ongoing activities of the Academy of Science of the Czech Republic and Charles University World Centre of Excellence in Landslide Risk Assessment.

Current state and use of the database

The current version of the GLOFs database is available online at glofs-database.org. As of October 2015, about one hundred GLOFs were presented on the website in a standard form. This is only one fifth of the total number of GLOFs so far collected from various data sources (Vilímek et al. 2014). The database is gradually being filled, region by region, as the data are validated. Data from the Peruvian Andes (regional database compiled by Zapata (2002), updated by Emmer et al. (2014); the Patagonian Andes (regional database for Argentina and Chile recently compiled by Anacona et al. 2015a); and the North American Cordillera (regional database compiled by Clague and Evans 2000; O'Connor et al. 2001) are represented in the database, while other regions of GLOFs (see Table 1) have not yet been validated, put into the form, and uploaded to the website. Unpublished data are available by request at the email address: glofs.database@gmail.com.

General aspects, limits, and challenges of database compilation

Databases of hazardous processes and glacial lake outburst floods

Driven by increasing data availability, global databases (or inventories) of different types of natural hazards and disasters have been created for different purposes such as basic research, hazard analysis and risk management, or (re)insurance (Wirtz et al. 2014; Huggel et al. 2015; Klose et al. 2015). Among those, the worldwide real-time database of earthquakes provided by USGS (earthquake.usgs.gov), and the NatCatSERVICE database of major disasters managed by Munich Reinsurance (Munich RE 2003) are the best-known. Global databases also exist for different types of slope movements (e.g., Malamud et al. 2004; Hewitt et al. 2008; Kirschbaum et al. 2010); however, regional databases are much more common (e.g., Blahůt et al. 2010; Havenith et al. 2015; Wood et al. 2015). A similar pattern is observed also for glacial lake outburst floods.

GLOFs have recently become one of the most studied hazardous consequences of the retreat of glaciers. A detailed inventory of GLOFs has already been compiled for Europe within the framework of the Glaciorisk project (Richard and Gay 2003), mentioning 333 GLOFs and ice avalanches in the Alps (most of them from ice-dammed lakes) and 85 in Iceland, and a separate database for glacier-related hazards in the Swiss Alps (glacierhazards.ch). Another inventory, for Central Asia, is provided by ICIMOD (Ives et al. 2010). One of the first attempts to create a global database of GLOFs was made for subaerial ice-dammed lake outburst floods (Walder and Costa 1996, mentions more than 120 cases, and for moraine-dammed lakes (O'Connor et al. 2001), mentions about 70 cases (some of them with repeated flooding). A number of GLOFs have been described within the frame of the GAPHAZ project (gaphaz.org) and World Glacier Monitoring Service (wgms.ch). A global database of glacial lakes of all types (Würmli 2012) mentions about 450 GLOFs, the majority of which (more than 80 %) emerged from ice-dammed lakes. To create the database on a global scale, regional databases represent the most valuable data source; their records, however, need to be unified, and updated with recent outburst events (see Fig. 1). Regional databases also need to be completed, with the detailed data published in case studies (e.g., estimated peak discharge, damages).

Table 1 Examples of regional databases of GLOFs and case studies from different regions

Region	Examples of regional databases		Examples of recent case studies	
	Content	Reference	GLOF	Reference
South America				
- Peruvian Andes	About 20 GLOFs described	Zapata (2002)	2010 GLOF from Lake No. 513	Carey et al. (2012) Klimeš et al. (2014) Vilímek et al. (2015)
- Patagonian Andes	More than 30 GLOFs (some of them repeated)	Anacona et al. (2015a)	1977 GLOF in Engano valley	Anacona et al. (2015b)
			2000 GLOF at Calafate glacier	Harrison et al. (2006)
North America				
- Mountain ranges of Alaska	18 GLOFs mentioned	Neal (2007)	Repeated GLOF at Bear glacier	Wilcox et al. (2014)
- Mountain ranges of British Columbia	11 GLOFs from moraine-dammed lakes	Clague and Evans (2000)	Repeated GLOF at Tulsequah glacier	Geertsema and Clague (2005)
- Cascade Range	12 GLOFs from moraine-dammed lakes	O'Connor et al. (2001)	–	–
Asia				
- Hindu Kush-Himalaya	15 GLOFs mentioned	Yamada (1998)	Repeated GLOF in Hilji stream	Kropáček et al. (2015)
	20 GLOFs from moraine-dammed lakes	Ding and Liu (1992)	Kedarnath GLOF in 2013	Das et al. (2015) Allen et al. (2015)
	34 GLOFs mentioned	Ives et al. (2010)		
- Tibet	11 GLOFs mentioned	Chen et al. (1999)	Guangxieco GLOF in 1988	Liu et al. (2014)
- Pamir	NA	–	Dasht GLOF in 2002	Mergili and Schneider (2011)
- Tien Shan	4 GLOFs described	Bolch et al. (2011)	2008 GLOF at the western Zyndan glacier lake	Narama et al. (2010)
- Karakorum	35 GLOFs from ice-dammed lakes	Hewitt (1982)	GLOFs in Karambar valley	Iturrizaga (2006)
- Caucasus	NA	–	Lake Bashkara repeated GLOFs	Petrakov et al. (2012)
Europe				
- The Alps	24 GLOFs (some of them repeated)	Haeberli (1983)	2004 GLOF from Gornersee lake	Roux et al. (2010)
	333 GLOFs and ice avalanches	Richard and Gay (2003)		
	More than hundred of GLOFs in Swiss part of Alps	Glacierhazards.ch	GLOF from Tete Rousse Glacier in 1892	Gilbert et al. (2012)
- Scandinavia	10 GLOFs from glacier-dammed lakes	Xu et al. (2015)	2004 GLOF in Tverrdalen valley	Breien et al. (2008)
- Iceland	85 GLOFs	Richard and Gay (2003)	1999 GLOF at Aolheimajokull	Staines and Carrvick (2015)

Scale

Glacial lake outburst floods can be investigated on three spatial scales (levels): (i) case study (particular event), (ii) regional scale (GLOFs within the specific region defined most commonly by a mountain range), and (iii) global scale. The GLOF database is designed on a global scale, i.e., it aims to contain all GLOFs that occurred worldwide and describe them by unified quantitative as well as qualitative characteristics (see Vilímek et al. 2014), allowing detailed analysis. The GLOF database is primarily filled from regional databases being continually updated with individual case studies. This allows us to search for regional specifics which may help in the natural hazard evaluation process. Some of these studies have already reflected this regional level (Würmli 2012; Emmer and Cochachin 2013) and have later helped to build a regionally oriented method for assessing glacial lake outburst flood hazards (Emmer and Vilímek 2014).

Fig. 1 An example of the impacts of recent lake outburst flood involving four lakes in the Artizon and Santa Cruz valleys (Cordillera Blanca, Peru), February 2012. The part of the affected valley bottom shown in the photograph is up to 400 m wide and 4.5 km long. This event is not mentioned in the existing regional databases, illustrating the need for their updating

GLOFs are complex phenomena and it is necessary to consider regional specifics in order to weight up all of the precursors and triggering factors influencing the final hazard evaluation. Analyses of triggering factors worldwide have also revealed the importance of slope movements as direct triggers of these outburst floods. Local research (Klimeš et al. 2015) has also indicated possible interactions between these floods and landslides in susceptible areas.

Various data sources and the recent increase in research

Data on particular glacial lake outburst floods are compiled from different types of data sources (see Vilímek et al. 2014), the most important, and also probably the most reliable of which are scientific papers (including both regional databases and case studies). The term "GLOF" has been broadly used since the 1990s and the amount of GLOF-related research has increased rapidly in recent years. Typing the keyword "GLOF" or "GLOFs" into the Web of Science database (WOS 2015) returned 115 records in October 2015, of which 56 (48.6 %) had been published in the previous 3 years (2013 or later; see Fig. 2). This ratio is similar also for the SCOPUS database (SCOPUS 2015) with 155 records, of which 75 have been published since 2013 (48.4 %). Some of these papers are characterized as case studies describing particular GLOF(s) (for examples see Table 1), some are characterized as methodological papers (e.g., Emmer and Vilímek 2014; Worni et al. 2014; Westoby et al. 2015), and some deal with modeling of potential lake outburst floods (Mergili et al. 2013; Nussbaumer et al. 2014; Klimeš et al. 2014; Emmer et al. 2015; Wang et al. 2015). Papers containing comprehensive regional databases of GLOFs are rare (e.g., Anacona et al. 2015a; Xu et al. 2015).

The number of described GLOFs is not only a matter of the frequency of occurrence of events but also a question of the level of scientific knowledge (compare, for example, Asia and Europe in Table 1). In Central Asia, there is probably still a high potential for describing new events, when compared to mountain ranges where natural phenomena are already well documented (e.g., the European Alps).

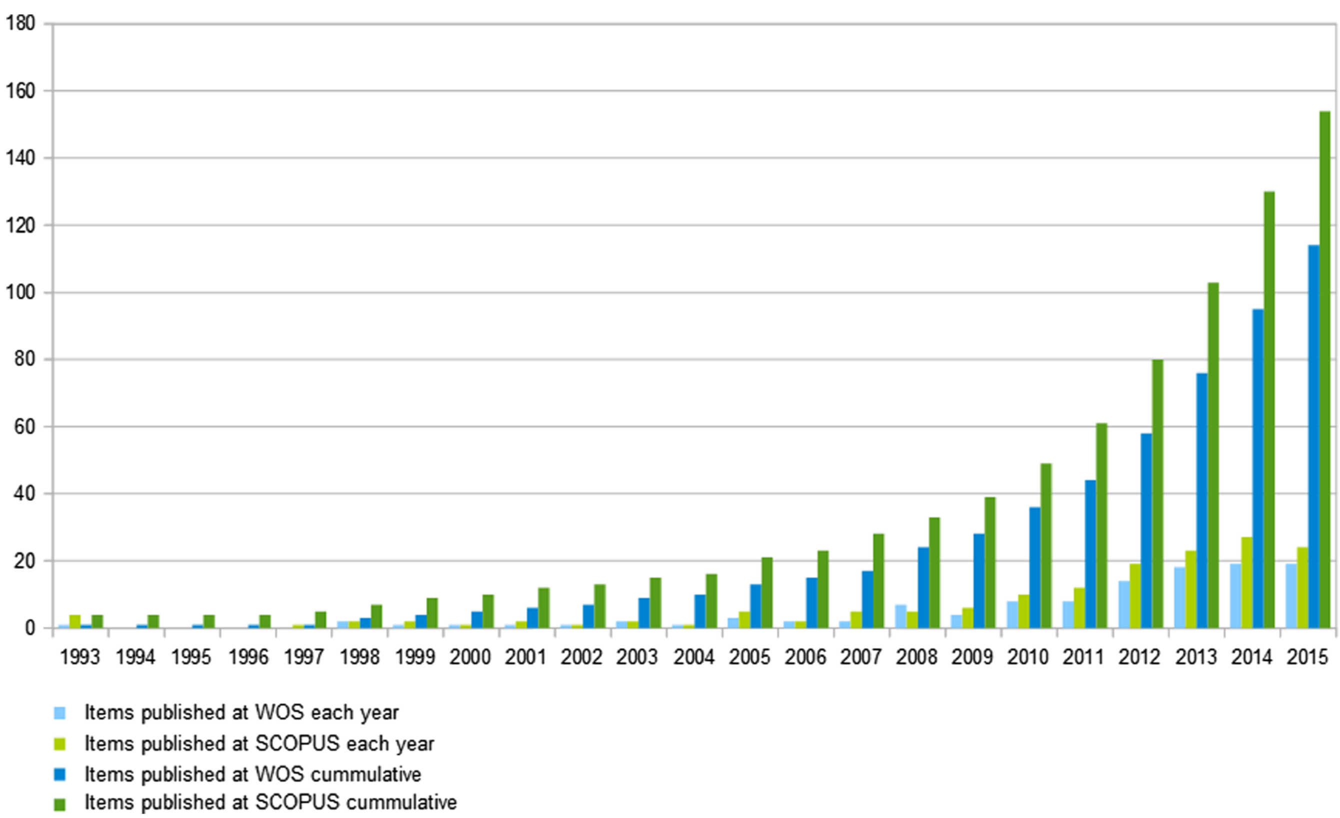

Fig. 2 Increasing number of GLOF-related articles published at Web of Science (*WOS*) and SCOPUS databases between 1993 and 2015 (as of October 2015)

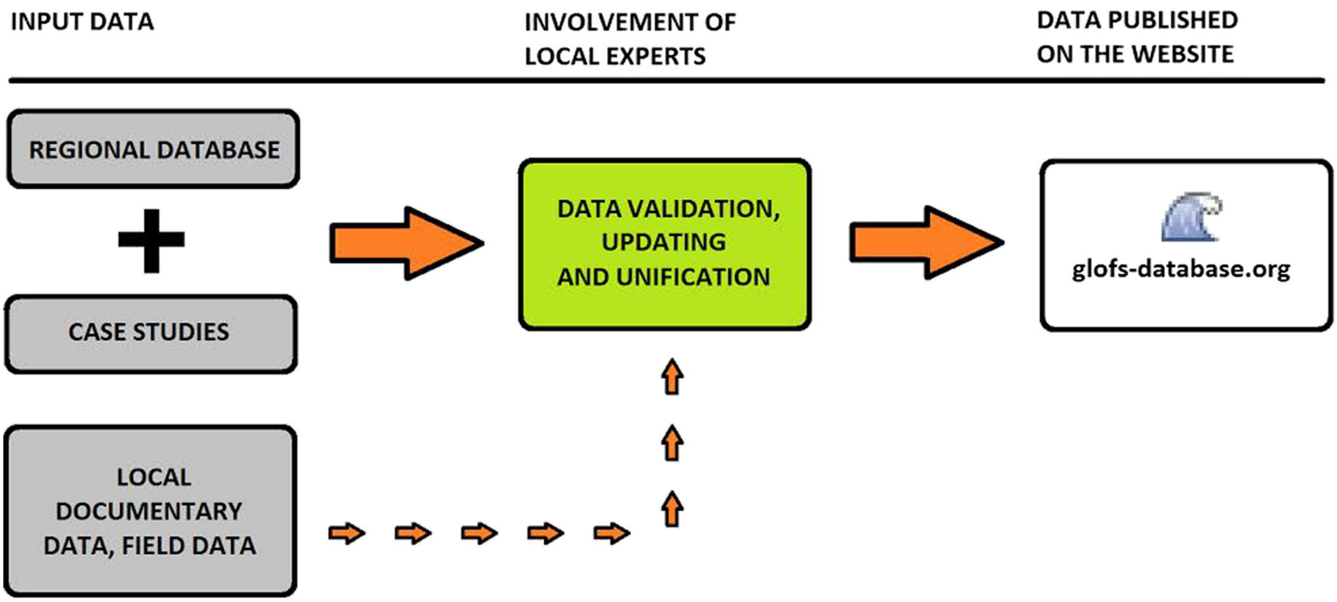

Fig. 3 Optimized procedure of database compilation with the involvement of local experts

Data validation: need for involvement of local experts

Different lake types and the variability of the causes and mechanisms of glacial lake outburst floods (e.g., Clague and Evans 2000) make a challenge out of attempts to provide a worldwide database. To cover the complexity, a versatile form has been designed (see Vilímek et al. 2014); however, existing regional databases do not usually provide sufficient information to complete an entire form for each GLOF event. Compilation and verification of all available data from various sources, including local documentary data and field data, is of high importance (e.g., Raška et al. 2014). The most important task for further development of the GLOFs database, therefore, is the involvement of local experts (or foreign experts with the appropriate regional knowledge) to validate the available data and, in optimal cases, also to provide different types of local documentary and field data (see Fig. 3).

Concluding remarks

Despite the limitations and barriers encountered during the compilation and development of the glacial lake outburst floods database, this project has received positive feedback from the scientific community. It has been a data source for a Master's thesis and several scientific papers. The increase in the number of publications on the topic of GLOFs during the last few years enhances the importance of the database. Probably its main significance can be seen on a regional level, where relevant issues can be inferred. We also cannot forget about the ongoing climate change, which can be an important driving force for future outburst floods on a global scale. The official duration of the project is until the end of 2015; nevertheless, filling, development, and maintenance of the database will continue as an activity of our World Centre of Excellence-Landslide Risk Assessment and Development Guidelines for Effective Risk Reduction. Involvement of local experts is highly important in data validation and a challenging issue in the future development of the database.

Acknowledgments

This research has been performed under the framework of IPL Project No. 179 and was financially supported by the Grant Agency of Charles University (GAUK Project No. 70 413) and by the Ministry of Education, Youth and Sports of the Czech Republic and within the National Sustainability Program I (NPU I), Grant No. LO1415 and INGO Grant No. LG15007.

References

Allen SK, Rastner P, Arora M, Huggel C, Stoffel M (2015) Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. Landslides not yet assigned issue. doi:10.1007/s10346-015-0584-3

Anacona PI, Mackintosh A, Norton KP (2015a) Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. Earth Surf Process Landf 40(1):2–21. doi:10.1002/esp.3524

Anacona PI, Mackintosh A, Norton KP (2015b) Reconstruction of a glacial lake outburst flood (GLOF) in the Engano Valley, Chilean Patagonia: lessons for GLOF risk management. Sci Total Environ 527:1–11. doi:10.1016/j.scitotenv.2015.04.096

Blahůt J, van Westen CJ, Sterlacchini S (2010) Analysis of landslide inventories for accurate prediction of debris-flow source areas. Geomorphology 119(1–2):36–51. doi:10.1016/j.geomorph.2010.02.017

Bolch T, Peters J, Yegorov A, Pradhan B, Buchroithner M, Blagoveshchensky V (2011) Identification of potentially dangerous glacial lakes in the northern Tien Shan. Nat Hazards 59(3):1691–1714. doi:10.1007/s11069-011-9860-2

Breien H, De Blasio FV, Elverhoi A, Hoeg K (2008) Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides 5(3):271–280. doi:10.1007/s10346-008-0118-3

Carey M, Huggel C, Bury J, Portocarrero C, Haeberli W (2012) An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. Clim Chang 112(3–4):733–767. doi:10.1007/s10584-011-0249-8

Chen C, Wang T, Zhang Z, Liu Z (1999) Glacial lake outburst floods in upper Nanchu River Basin, Tibet. J Cold Reg Eng 13(4):199–212

Clague JJ, Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat Sci Rev 19(17–18):1763–1783. doi:10.1016/S0277-3791(00)00090-1
Das S, Kar NS, Bandyopadhyay S (2015) Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. Nat Hazards 77(2):769–786. doi:10.1007/s11069-015-1629-6
Ding Y, Liu J (1992) Glacial lake outburst flood disasters in China. Ann Glaciol 16:180–184
Emmer A, Cochachin AR (2013) The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera and Himalaya. AUC Geographica 48(2):5–15
Emmer A, Vilímek V (2014) New method for assessing the susceptibility of glacial lakes to the outburst floods in the Cordillera Blanca, Peru. Hydrol Earth Syst Sci 18:3461–3479. doi:10.5194/hess-18-3461-2014
Emmer, A., Vilímek, V., Klimeš, J., Cochachin, A. (2014): Glacier retreat, lakes development and associated natural hazards in the Cordillera Blanca (Peru). In W.Shan et al. (eds.) Landslides in Cold Regions in the Context of Climate Change; Springer, Springer International Publishing Switzerland. pp 231–252. doi: 10.1007/978-3-319-00867-7_17
Emmer A, Merkl S, Mergili M (2015) Spatio-temporal patterns of high-mountain lakes and related hazards in western Austria. Geomorphology 246:602–616. doi:10.1016/j.geomorph.2015.06.032
Geertsema M, Clague JJ (2005) Jökulhlaups at Tulsequah Glacier, northwestern British Columbia, Canada. The Holocene 15(2):310–316. doi:10.1191/0959683605hl812rr
Gilbert A, Vincent C, Wagnon P, Thibert E, Rabatel A (2012) The influence of snow cover thickness on the thermal regime of Tete Rousse Glacier (Mont Blanc range, 3200 m a.s.l.): consequences for outburst flood hazards and glacier response to climate change. J Geophys Res-Earth Surface 117:F04018. doi:10.1029/2011JF002258
Haeberli W (1983) Frequency characteristics of glacier floods in The Swiss Alps. Ann Glaciol 4:85–90
Harrison S, Glasser NF, Winchester V, Haresign E, Warren C, Jansson K (2006) A glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. The Holocene 16(4):611–620. doi:10.1191/0959683606hl957rr
Havenith HB, Strom A, Torgoev I, Lamair L, Ischuk A, Abdrakhmatov K (2015) Tien Shan geohazards database: earthquakes and landslides. Geomorphology 249:16–31. doi:10.1016/j.geomorph.2015.01.037
Hewitt K (1982) Natural dams and outburst floods of the Karakoram Himalaya. In Glen JW (Ed) hydrological aspects of alpine and high mountain areas. International Association of Hydrological Sciences (IAHS), Great Yarmouth (UK), pp 259–269
Hewitt K, Clague JJ, Orwin JF (2008) Legacies of rock slope failures in mountain landscapes. Earth Sci Rev 87(1–2):1–38. doi:10.1016/j.earscirev.2007.10.002
Huggel C, Raissig A, Rohrer M, Romero G, Diaz A, Salzmann N (2015) How useful and reliable are disaster databases in the context of climate and global change? A comparative case study analysis in Peru. Nat Hazards Earth Syst Sci 15(3):475–485. doi:10.5194/nhess-15-475-2015
Iturrizaga L (2006) Key forms for reconstructing glacier dams, lakes and outburst floods: historical ice-dammed lakes in the Karambar Valley, Hindukush (Pakistan). Zeitschrift für Geomorphologie Supplement Serie 142:361–388
Ives JD, Shrestha BR, Mool PK (2010) Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu
Kirschbaum DB, Adler R, Hong Y, Hill S, Lerner-Lam A (2010) A global landslide catalog for hazard applications: method, results, and limitations. Nat Hazards 52(3):561–575. doi:10.1007/s11069-009-9401-4
Klimeš J, Benešová M, Vilímek V, Bouška P, Cochachin AR (2014) The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. Nat Hazards 71(3):1617–1638. doi:10.1007/s11069-013-0968-4
Klimeš J., Vilímek V., Benešová M. (2015): Landslide and glacial lake outburst flood hazard in the Chucchún river basin, Cordillera Blanca, Peru. AUC Geographica 50(2):173–180.: doi: 10.14712/23361980.2015.96
Klose M, Damm B, Highland LM (2015) Databases in geohazard science: an introduction. Geomorphology 249:1–3. doi:10.1016/j.geomorph.2015.06.029
Kropáček J, Neckel N, Tyrna B, Holzer N, Hovden A, Gourmelen N, Schneider C, Buchroithner M, Hochschild V (2015) Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal. Nat Hazards Earth Syst Sci 15:2425–2437. doi:10.5194/nhess-15-2425-2015
Liu JJ, Cheng ZL, Li Y (2014) The 1988 glacial lake outburst flood in Guangxieco Lake, Tibet, China. Nat Hazards Earth Syst Sci 14(11):3065–3075. doi:10.5194/nhess-14-3065-2014
Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004) Landslide inventories and their statistical properties. Earth Surf Process Landf 29(6):687–711. doi:10.1002/esq.1064
Mergili M, Schneider JF (2011) Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Nat Hazards Earth Syst Sci 11(5):1447–1462. doi:10.5194/nhess-11-1447-2011
Mergili M, Muller JP, Schneider JF (2013) Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). Glob Planet Chang 107:13–24. doi:10.1016/j.gloplacha.2013.04.001
Munich RE (2003) NatCatSERVICE a guide to the Munich Re database for natural catastrophes. Munich Reinsurance Company, Munich
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. Nat Hazards Earth Syst Sci 10(4):647–659
Neal EG (2007) Hydrology and glacier-lake outburst floods (1987–2004) and water quality (1998–2003) of the Taku River near Juneau, Alaska. U.S. Geological Survey, Reston, Virginia
Nussbaumer S, Schaub Y, Huggel C, Walz A (2014) Risk estimation for future glacier lake outburst floods based on local land-use changes. Nat Hazards Earth Syst Sci 14(6):1611–1624. doi:10.5194/nhess-14-1611-2014
O'Connor JE, Hardison JH, Costa JE (2001) Debris flows from failures of neoglacial-age moraine dams in the Three Sisters and Mount Jefferson Wilderness Areas. Geological Survey, Reston, Virginia, Oregon. U.S
Petrakov DA, Tutubalina OV, Aleinikov AA, Chernomorets SS, Evans SG, Kidyaeva VM, Krylenko IN, Norin SV, Shakhmina MS, Seynova IB (2012) Monitoring of bashkara glacier lakes (central Caucasus, Russia) and modelling of their potential outburst. Nat Hazards 61(3):1293–1316. doi:10.1007/s11069-011-9983-5
Raška P, Zábranský V, Dubšiar J, Kadlec A, Hrbáčová A, Strnad T (2014) Documentary proxies and interdisciplinary research on historic geomorphologic hazards: a discussion of the current state from a central European perspective. Nat Hazards 70(1):705–732. doi:10.1007/s11069-013-0839-z
Richard & Gay (2003) GLACIORISK. Survey and prevention of extreme glaciological hazards in European mountainous regions. EVG1 2000 00512 Final report (01.01.2001–31.12.2003)
Roux PF, Walter F, Riesen P, Sugiyama S, Funk M (2010) Observation of surface seismic activity changes of an Alpine glacier during a glacier-dammed lake outburst. J Geophys Res Earth Surf 115:F03014. doi:10.1029/2009JF001535
Sassa K (2012) ICL strategic plan 2012–2021—to create a safer geo-environment. Landslides 9(2):155–164. doi:10.1007/s10346-012-0334-8
Staines KEH, Carrvick JL (2015) Geomorphological impact and morphodynamic effects on flow conveyance of the 1999 jokulhlaup at Solheimajokull, Iceland. Earth Surf Process Landf 40(10):1401–1416. doi:10.1002/esp.3750
Vilímek V, Emmer A, Huggel C, Schaub Y, Würmli S (2014) Database of glacial lake outburst floods (GLOFs)—IPL Project No. 179. Landslides 11(1):161–165. doi:10.1007/s10346-013-0448-7
Vilímek V, Klimeš J, Emmer A, Benešová M (2015) Geomorphologic impacts of the glacial lake outburst flood from Lake No. 513 (Peru). Environmental Earth Sciences 73:5233–5244. doi:10.1007/s12665-014-3768-6
Walder JS, Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. Earth Surf Process Landf 21(8):721–723
Wang W, Gao Y, Anacona PI, Lei Y, Xiang Y, Zhang G, Li S, Lu A (2015) Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley. Central Himalayas Geomorphol not yet assigned issue. doi:10.1016/j.geomorph.2015.08.013
Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM, Hassan MAAM, Lowe A (2015) Numerical modelling of glacial lake outburst floods using physically based dam-breach models. Earth Surface Dynamics 3(1):171–199. doi:10.5194/esurf-3-171-2015
Wilcox AC, Wade AA, Evans SG (2014) Drainage events from a glacier-dammed lake, Bear Glacier, Alaska: remote sensing and field observations. Geomorphology 220:41–49. doi:10.1016/j.geomorph.2014.05.025
Wirtz A, Kron W, Low P, Steuer M (2014) The need for data: natural disasters and the challenges of database management. Nat Hazards 70(1):135–157. doi:10.1007/s11069-012-0312-4
Wood JL, Harrison S, Reinhardt L (2015) Landslide inventories for climate impacts research in the European Alps. Geomorphology 228:398–408. doi:10.1016/j.geomorph.2014.09.005
Worni R, Huggel C, Clague JJ, Schaub Y, Stoffel M (2014) Coupling glacial lake impact, dam breach, and flood processes: a modeling perspective. Geomorphology 224:161–176. doi:10.1016/j.geomorph.2014.06.031

Würmli S (2012) Ausbruchmechanismen von hochalpinen Seen – ein weltweites Inventar. University of Zürich, Magister thesis

Xu MZ, Bogen J, Wang ZY, Bonsnes TE, Gytri S (2015) Pro-glacial lake sedimentation from jokulhlaups (GLOF), Blamannsisen, northern Norway. Earth Surf Process Landf 40(5):654–665. doi:10.1002/esp.3664

Yamada T (1998) Glacier lake and its outburst flood in the Nepal Himalaya. Japanese Society of Snow and Ice. Tokyo, Japan

Zapata ML (2002) La dinamica glaciar en lagunas de la Cordillera Blanca. Acta Montana ser A Geodynamics 19(123):37–60

Online sources

earthquake.usgs.gov. Earthquake hazard program. Accessed 4 November 2015.

gaphaz.org. Database of glacier and permafrost disasters. Accessed 4 November 2015.

glacierhazards.ch Glacier hazards database for Swiss Alps. Accessed 4 November 2015.

glofs-database.org. Database of glacial lake outburst floods. Accessed 4 November 2015.

SCOPUS (2015) Abstract and citation database. Elsevier. www.scopus.com. Accessed 2 November 2015

wgms.ch. World Glacier Monitoring Service (WGMS). Accessed 4 November 2015.

WOS (2015) Web of knowledge. Thomson Reuters. www.webofknowledge.com. Accessed 2 November 2015

A. Emmer · V. Vilímek (✉)
Department of Physical Geography and Geoecology,
Faculty of Science, Charles University in Prague,
Albertov 6, 128 43, Prague 2, Czech Republic
e-mail: vit.vilimek@natur.cuni.cz

A. Emmer
e-mail: aemmer@seznam.cz

A. Emmer
Department of the Human Dimensions of Global Change,
Global Change Research Institute, The Czech Academy of Sciences,
Bělidla 986/4a, 603 00 Brno, Czech Republic
e-mail: aemmer@seznam.cz

C. Huggel · Y. Schaub
Glaciology and Geomorphodynamics Group,
Division of Physical Geography, Department of Geography,
University of Zürich, Winterthurerstrasse, 190, 8057 Zürich, Switzerland

J. Klimeš
Institute of Rock Structure and Mechanics,
The Czech Academy of Sciences,
V Holešovičkách 41, 182, 09 Prague 8,
Czech Republic