Supplementary Material

Evaluation of Glacial Lake Outburst Flood susceptibility using multi-criteria assessment framework in Mahalangur Himalaya

Nitesh Khadka[1,2], Xiaoqing Chen[1,3,*], Yong Nie[1], Sudeep Thakuri[4], Guoxiong Zheng[2,5], Guoqing Zhang[3,6]

[1]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

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

[3]CAS Center for Excellence in Tibetan Plateau Earth Sciences, CAS, Beijing 100101, China

[4]Central Department of Environmental Science, Tribhuvan University, Kritipur, Kathmandu, Nepal

[5]Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

[6]Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

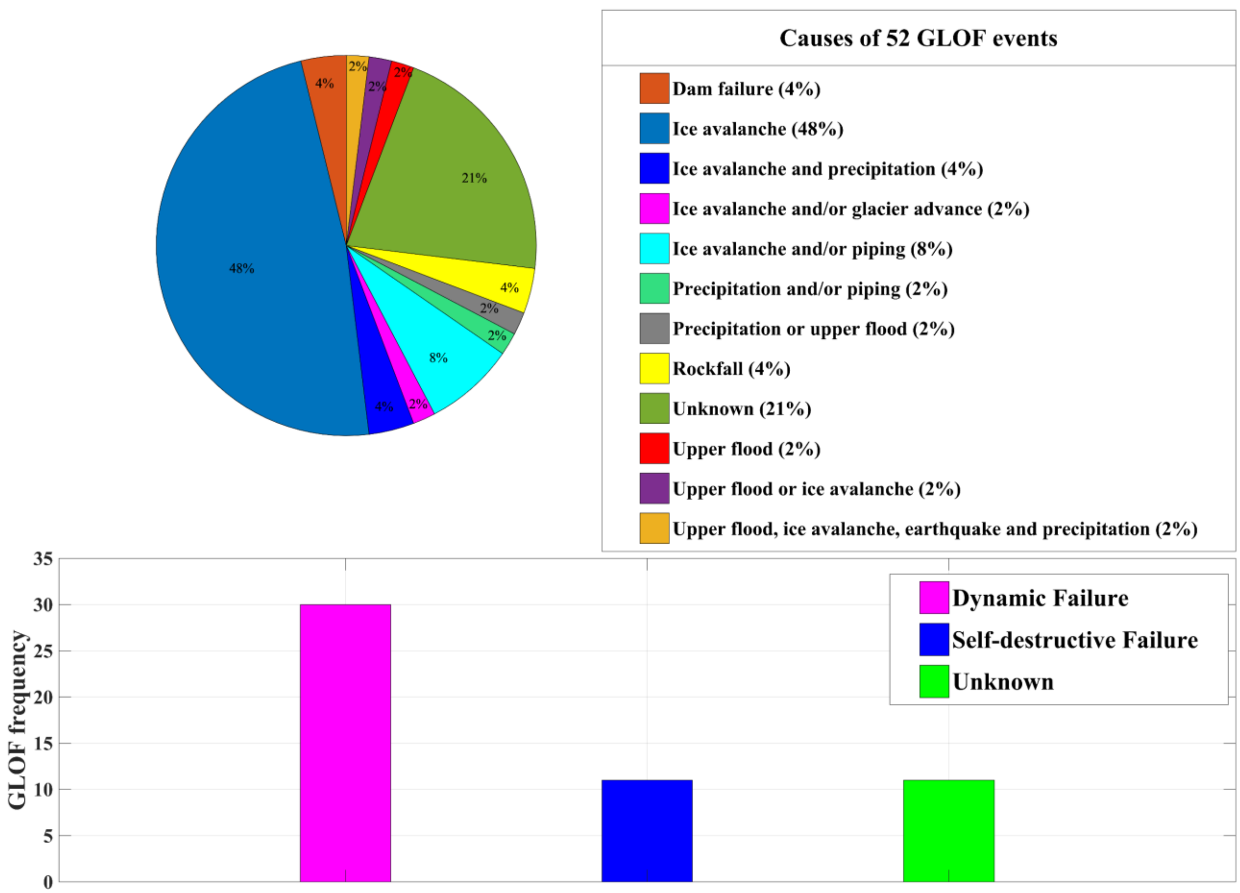

Figure S1. Causes of 52 GLOF events recorded across the Himalaya (after Nie et al. (2018); Byers et al. (2018)). Dynamic failure is resulted to failure from mass movement into the lake while self-destructive failure is related with failure of the moraine from hydrostatic pressure, buried ice or dam degradation with time.

Table S1. Potential factors that govern the mechanism for GLOF. Here, F1-F7 represent lake-glacier characteristics, F8-F16 represent dam characteristics, F17-19 represent surrounding characteristics, F20-F23 represent other characteristics. These factors well govern the mechanism of failure (dam overtopping or dam failure), and many studies select suitable factors among them to analyze GLOF hazard. Here, we selected F2, F4 and F5 to represent the lake and glacier characteristics, F8-F9 to represent dam characteristics, and F17-F19 to represent surrounding features and mass movements. However, factors F18 and F19 were merged to avoid overlapping, and other factors were not used as they were redundant and were difficult to analyze from remote sensing.

No.	Factor	Definition	Sources
F1	Altitude (m a.s.l.)	Lake height above sea level	(Huggel et al., 2004; Worni et al., 2013; Nie et al., 2018; Rounce et al., 2016; Prakash and Nagarajan, 2017; Allen et al., 2019)
F2	Lake area	Surface area digitized from satellite images	
F3	Volume (×10^6 m^2)	Amount of water stored in the lake	
F4	Expansion rate	Expansion rate of lake area	
F5	Glacier-lake distance	Horizontal distance between the lake and its parent glacier	
F6	Area of mother glacier	Surface area of feeding glacier	
F7	Slope between the lake and glacier	Slope between the lake and its parent glacier	
F8	Dam types (moraine, rock, ice-dammed or other dams)	Lakes dammed by weak moraine, stable rock and unstable ice	
F9	Moraine dam steepness [Steep Lake-Front Area (SLA) Slope]	Dam slope of the lakefront identified from highest to the lowest elevation	
F10	Ice-cored moraine dam	Dead ice underneath moraine	
F11	Dam freeboard	Height difference between lake water and crest of dam	
F12	Moraine width to height ratio	Ratio between width and height of moraine	
F13	Distal slope face of the moraine	Slope of moraine distal face	
F14	Width of crest	Horizontal distance of dam crest	
F15	Moraine slopes stabilized by vegetation	Vegetation cover on terminal moraine	
F16	Remedial works	Lake lowering projects implemented	
F17	Ice avalanche	Ice/snow breaks within the watershed of the lake with probability to hit lake	
F18	Rockfall/landslides	Earth materials break within the watershed of the lake with probability to hit lake	
F19	Upstream GLOF	Outburst from lakes located upstream of other	
F20	Extreme rainfall events	Days with greater intensity of rainfall (R10 and R25 mm days)	
F21	Seismic activity (Earthquake)	Violent shaking of the ground	
F22	Upstream watershed area of the lake	The area or ridge of land from where water accumulates into the lake	
F23	Historical GLOFs	Recorded events of GLOFs	

Table S2. Historical GLOFs in the Himalaya with their details and susceptibility index calculated from the method of this study.

Lake name	Outburst date	*Lake area (km^2)	*Expansion rate	Cause of triggers	Glacier-lake distance (m)	Trend after burst	Dam characteristics	Source	#Susceptibility index
Nare lake	03-09-1977	-	-	-	0	0	Moraine	Nie et al., (2018)	-
Nagma Pokhari	23-06-1980	1.1	high (75%)	Ice Avalanche	0	stable	Moarine end	Byers et al., (2020)	1
Unknown	1999	0.022	high	unknown	700	disappeared	Moriane	Veh et al., (2019)	-
Tiptola	1963/1968	0.15	unknown	unknown	0		Moraine	Byers et al., (2020)	-
Kongyangmi La Tsho	1997	0.52	low	Ice Avalanche	0	stable	Moraine	Nie et al., (2018)	0.91
Chorabari lake	17-06-2013	0.05	low	extreme ppt	<500	disappeared	Moraine	Nie et al., (2018)	-
Luggye Tsho	7-10-1994	1.12	unknown	landslide	0	expanded	Moraine	Nie et al., (2018)	0.88
Gangri Tsho	1998	0.24	low	Ice Avalanche	<500	stable	Moraine	Nie et al., (2018)	0.85
Lemtheng Tsho	28-06-2015	0.06	med	upper flood and ice-avalanche	0	disappeared	Moraine	Nie et al., (2018)	0.8
Dig Tsho	4-8-1985	0.5	high	Ice Avalanche	0	expanded	End-moraine with steep slope	Vuichard and Zimmermann, 1987	0.94

Tam Pokhari	3-9-1998	0.45	low	Avalanche and	0	stable	End-moraine with steep slope	Lamsal et al., 2016b	0.89
Langmale	20-04-2017	0.08	high	Rockfall	0	reduced	End-moraine with the steep slope	Byers et al., 2018	0.97

Table S3. Final result of two-way expert (*n*=11) comparison matrix.

Class [c]	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**
Avalanche (F1)	1	1	4	3	4	4
SLA (F2)	1	1	0.5	3	4	4
Rockfall (F3)	0.25	2	1	3	3	4
Lake expansion (F4)	0.333	0.333	0.333	1	3	4
Glacier lake proximity (F5)	0.25	0.25	0.333	0.333	1	3
Lake area (F6)	0.25	0.25	0.25	0.25	0.333	1
Total	**3.083**	**4.833**	**6.416**	**10.583**	**15.333**	**20**

Here, 1=equal, 2=weak, 3=moderate, 4=important

Table S4. Normalizing matrix and calculation of factor weights.

Class	**F1**	**F2**	**F3**	**F4**	**F5**	**F5**	**Sum**	**Factor weight (w)**
F1	0.324	0.207	0.623	0.283	0.261	0.2	1.898	**0.32**
F2	0.324	0.206	0.078	0.283	0.261	0.2	1.353	**0.23**
F3	0.081	0.413	0.15	0.283	0.195	0.2	1.329	**0.22**
F4	0.108	0.0689	0.0519	0.094	0.196	0.2	0.719	**0.12**
F5	0.081	0.0517	0.052	0.0314	0.065	0.15	0.431	**0.07**
F6	0.081	0.051	0.038	0.0236	0.022	0.05	0.267	**0.04**
Total	1	1	1	1	1	1	6	1

Table S5. Calculation of consistency ratio.

Class	Ws= [c].[w]	Consistency= [Ws].[1/w]	CI=(Lyambda-n)/(n-1)	RI	CR= CI/RI
F1	2.254	7.121	0.123	1.24	0.091 9.91%
F2	1.478	6.553			
F3	1.505	6.791			
F4	0.768	6.409			
F5	0.454	6.324			
F6	0.289	6.499			
Total		39.700			
Average (lyambda)		6.617			

Here, Ws=matrix multiplication; CI=consistency index; RI=ratio index; CR=consistency ratio

Table S6. Expansion rates of three typical glacial lakes (1998-2018)

Lake ID	**Lake name**	**Longitude (°)**	**Latitude (°)**	**1998 area (km²)**	**2018 area (km²)**	**Expansion rate (%)**
M32	Imja Tsho	86.926	27.898	0.71	1.45	104
M24	Lumding Tsho	86.612	27.779	0.78	1.29	65
M47	Barun Tsho	87.087	27.796	0.85	1.92	125

Table S7. Sixty-four glacial lakes with their GLOF class based on GLOF susceptibility evaluation. Here, 0, 1, 2, 3 and 4 represent very low, low, medium, high, and very high GLOF susceptibility.

Lake ID	Longitude (°)	Latitude (°)	Area (km^2)	Dam type*	GLOF class
M0	86.56580353	27.95330048	0.047	I	1
M1	86.65119934	27.94619942	0.064	R	1
M2	87.06950378	27.6977005	0.054	R	1
M3	87.29160309	27.84210014	0.069	R	1
M4	87.33209991	27.82419968	0.054	R	0
M5	87.20639801	27.69099998	0.105	R	1
M6	86.84960175	27.6086998	0.084	R	1
M7	86.7098999	28.03790092	0.147	R	2
M8	86.68240356	28.02490044	0.093	M	1
M9	86.72119904	28.01720047	0.175	M	0
M10	86.68219757	28.00569916	0.162	M	1
M11	86.83570099	27.99720001	0.106	M	2
M12	86.64910126	27.9885006	0.048	R	2
M13	86.6812973	27.97520065	0.559	M	1
M14	86.69020081	27.95089912	0.412	M	1
M15	86.6989975	27.94099998	0.175	M	1
M16	86.74639893	27.93309975	0.064	M	2
M17	86.68299866	27.89579964	0.124	R	2
M18	86.58599854	27.87409973	0.388	M	3
M19	86.84429932	27.81080055	0.056	R	1

M20	86.62090302	27.79050064	0.434	M	4
M21	86.86730194	27.77770042	0.050	M	1
M22	86.64299774	27.77759933	0.278	R	2
M23	86.8710022	27.76619911	0.135	I	2
M24	86.61109924	27.77890015	1.289	M	4
M25	86.86360168	27.75979996	0.058	M	1
M26	86.83879852	27.79339981	0.252	I	4
M27	86.84470367	27.74259949	0.242	M	2
M28	86.59940338	27.71139908	0.096	M	2
M29	86.792099	27.69630051	0.125	R	2
M30	86.85870361	27.68720055	0.301	M	3
M31	86.85359955	27.68090057	0.101	M	3
M32	86.9265976	27.89830017	1.444	M	2
M33	86.9138031	27.89389992	0.103	M	2
M34	86.89720154	27.88660049	0.052	R	3
M35	86.93779755	27.85700035	0.201	M	2
M36	86.91870117	27.85659981	0.066	M	1
M37	86.92870331	27.85009956	0.408	M	2
M38	87.08159637	27.84410095	0.391	M	3
M39	86.93560028	27.83690071	0.269	M	1
M40	86.95140076	27.84009933	0.062	M	0
M41	86.91739655	27.83250046	0.307	M	2
M42	87.09539795	27.82900047	0.110	M	2
M43	87.06549835	27.82859993	0.052	M	3
M44	86.91480255	27.82789993	0.045	M	1
M45	86.95539856	27.81760025	0.061	M	3
M46	86.97429657	27.80540085	0.156	M	2
M47	87.09169769	27.79780006	1.918	M	4
M48	86.96649933	27.79910088	0.183	M	1
M49	86.91110229	27.79430008	0.168	M	0
M50	86.94249725	27.79680061	0.051	M	1
M51	86.95709991	27.78300095	0.743	M	4
M52	86.95890045	27.7548008	0.832	M	4
M53	86.91040039	27.71929932	0.123	M	4
M54	86.91649628	27.71360016	0.060	R	1
M55	86.85440063	27.64760017	0.047	M	1
M56	86.98300171	27.63669968	0.068	R	1
M57	86.78679657	27.92359924	0.522	M	1
M58	86.88809967	27.75729942	0.061	M	3
M59	86.70069885	27.95269966	0.089	I	1
M60	86.80400085	27.97450066	0.197	I	2
M61	86.67539978	27.92079926	0.047	M	3
M62	86.63249969	27.78840065	0.055	R	3
M63	86.54930115	27.94389915	0.061	M	3

*I=ice-dammed; M=Moraine dammed; R= Bed-rock dammed

Table S8. Comparison of mean differences of lake delineation between this and previous studies.

Study	Data	Delineated year	Number of lakes compared	Δ from this study* (km^2)	
				Mean Differences	Standard Deviation
Khadka et al. (2018)	Landsat (30 m)	2017	234	-0.007	0.2
Zhang et al. (2015)	Landsat (30 m)	2009	58	-0.04	0.35
Maharjan et al. (2018)	Landsat (30 m)	2005	240	0.008	0.2
This study	Pleiades image (0.5 m)	2018	31	-0.02	0.2

* Negative Δ indicates this study (area delineated from Sentinel-2 imagery) has a lower area than the previous study.

References

Allen, S. K., Zhang, G. Q., Wang, W. C., Yao, T. D. & Bolch, T. (2019) Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin,* 64**,** 435-445.

Byers, A. C., Chand, M. B., Lala, J., Shrestha, M., Byers, E. A. & Watanabe, T. (2020) Reconstructing the History of Glacial Lake Outburst Floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An Interdisciplinary Approach. *Sustainability,* 12**,** 5407.

Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A. & Regmi, D. (2018) A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. *Landslides***,** 1-17.

Emmer, A. & Vilímek, V. (2013) Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). *Natural Hazards and Earth System Sciences,* 13**,** 1551.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D. & Richardson, S. (2004) An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal,* 41**,** 1068-1083.

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

Maharjan, S. B., Mool, P. K., Lizong, W., Xiao, G., Shrestha, F., Shrestha, R. B., Khanal, N. R., Bajracharya, S. R., Joshi, S., Shahi, S. & Baral, P. 2018. The status of glacial lakes in the Hindu Kush Himalaya. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Nie, Y., Liu, Q., Wang, J., Zhang, Y., Sheng, Y. & Liu, S. (2018) An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis. *Geomorphology,* 308**,** 91-106.

Prakash, C. & Nagarajan, R. (2017) Outburst susceptibility assessment of moraine-dammed lakes in Western Himalaya using an analytic hierarchy process. *Earth Surface Processes and Landforms*.

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

Veh, G., Korup, O., von Specht, S., Roessner, S. & Walz, A. (2019) Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nature Climate Change,* 9**,** 379.

Worni, R., Huggel, C. & Stoffel, M. (2013) Glacial lakes in the Indian Himalayas—From an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Science of the Total Environment*, 468**,** S71-S84.

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