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Supplementary information

High Mountain Asia hydropower systems threatened by climate-driven landscape instability

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Supplementary Information for

High Mountain Asia hydropower systems threatened by climate-driven landscape instability

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Supplementary Tables

Supplement Table S1. A summary of historical hydropower project (HPP)-related hazards in HMA including hydropower dam failure or damage (light grey shaded), reservoir sedimentation (grey shaded), and turbine abrasion (dark grey shaded). GLOF, glacial lake outburst flood; LLOF, landslide lake outburst flood. '+' represents HPP under construction. This database reflects the available information from the existing literature and should not be interpreted as representing all the HPP-related hazards in HMA.

Time	Hazard name or place	Hazard type	Hydropower project (HPP)	Impacts on HPP	Country	Reference
2021.02	Chamoli flood	Rock-ice avalanche-flood	Rishiganga HPP and Tapovan V. HPP (+)	HPP failure	India	ref.[1]
2019.07	Rogheli Gol GLOF	GLOF	Golen Gol HPP (+)	Damage to intake of HPP	Pakistan	This study
2018.11	Baige landslide	LLOF	Suwalong HPP (+)	HPP failure (removal in advance)	China	ref.[2]
2016.07	Gongbatongsha Tsho GLOF	GLOF	Upper Bhotekoshi HPP	HPP failure	China/Nepal	ref.[3]
2015.07	Reshun GLOF	GLOF	Reshun Gol HPP	HPP failure	Pakistan	This study
2014.08	Jure Landslide	Landslide-flood	Unknown HPP (5 MW)	HPP failure	Nepal	ref.[4]
2013.07	Kedarnath flood	GLOF-Landslide-flood	>10 HPPs	HPP failure/damage	India	ref.[5]
2012.05	Seti flood	Rockfall-flood	Upper Seti HPP (25 MW)	Damage to intake of HPP	Nepal	ref.[6]
2002.05	Jialongco GLOF	GLOF (ice avalanche)	Unknown HPP	HPP failure	China	ref.[7]
1985.04	Dig Tsho GLOF	GLOF (ice avalanche)	Namche HPP (+)	HPP failure	China/Nepal	ref.[8]
1981.06	Zharico GLOF	GLOF (ice avalanche)	Unknown HPP	HPP failure	China	ref.[7]
1981.07	Cirenmaco-2 GLOF	GLOF (ice avalanche)	Sun Koshi HPP	HPP failure	China/Nepal	ref.[7]
1977.09	Nare Lake GLOF	GLOF	Unknown HPP	HPP failure	Nepal	ref.[7]
1977.08	Ulken Almaty GLOF	GLOF	Ulken Almaty HPP	Damage to canal of HPP	Kazakhstan	ref.[9]
2002-2012	Gandaki River	Reservoir sedimentation	Kali Gandaki-A HPP	Pondage capacity reduced by 50%	Nepal	ref.[10]
1982-2004	Kulekhani	Reservoir sedimentation	Kulekhani I Reservoir	The Kulekhani reservoir received 5.1 million m^3 of sediment due to rainstorm-induced landslides and debris flows in 1993 (540 mm rainfall in 24 hours), which represents ~25% of the reservoir sedimentation for 1982-2004	Nepal	ref.[10,11]

1974-2006	Tarbela	Reservoir sedimentation	Tarbela Reservoir	Storage capacity reduced by ~30%	Pakistan	ref.[12]
1967-2005	Mangla	Reservoir sedimentation	Mangla Reservoir	Storage capacity reduced by >20%	Pakistan	ref.[13]
1959-	Sultej River, Himachal Pradesh	Reservoir sedimentation	Bhakra Reservoir	Sedimentation rate was 2.5 times higher than original design	India	ref.[14]
2001-	Nianchu River, Tibet	Reservoir sedimentation	Manla Reservoir	Very high sedimentation rate	China	This study
2002-2012	Gandaki River	Turbine abrasion	Kali Gandaki-A HPP	All three turbines replaced after a few years' operation	Nepal	ref.[10]
2008.08	Tien Shan	Turbine abrasion	Tagake HPP	Turbines stopped functioning in 2008	China	This study
2005	Sultej River, Himachal Pradesh	Turbine abrasion	Nathpa Jhakri HPP	Turbines replaced after less than one year operation	India	ref.[12]

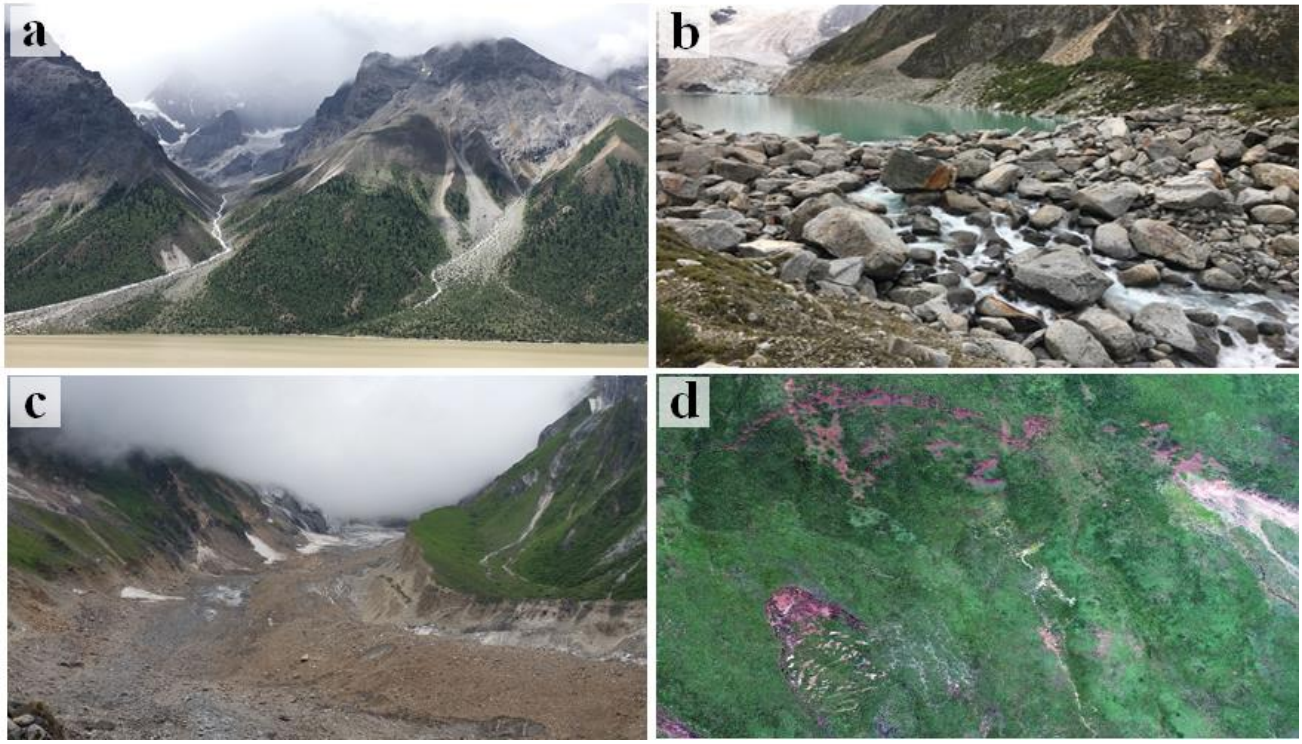
Supplementary Table S2. A summary of historical landslide lake outburst floods[15]. This database (1880-2020) is based on the available information from China (Yunnan, Tibet, Sichuan, Qinghai, Gansu, Xijiang). Similar information in other HMA countries needs to be collected further. Note that 50 of 83 reported events were reported after the 1980s.

Time	Longitude(E)	Latitude(N)	Landslide	Blocking duration	Location	Blocked river
1881.3.5	102°58'1.81"	26°50'25.49"	Shigaodi	3 days	Qiaojia, Yunnan	Jinsha River
1887.3.17	103°48'45.50"	28°16'05.32"	Wujiawan	7 days	Yongshan, Yunnan	Jinsha River
1902.7.8	94°56'23.20"	30°10'43.52"	Zhamunongba		Bomi, Tibet	Yigong Tsangpo River
1917.5	102°41'16.43"	29°20'01.00"	Baiyanhe		Hanyuan, Sichuan	Dadu River
1921.7.18	102°39'16.77"	26°11'06.25"	Pufu	Brief	Luquan, Yunnan	Pufu River
1927	102°40'32.83"	35°47'34.24"	Mengda		Xunhua, Qinghai	Yellow River
1933.8.25	103°41'07.35"	32° 01'25.77"	Diexi	45 days	Mao, Sichuan	Min River
1933.8.25	103°38'25.86"	32° 05'13.01"	Shangbailazhai		Mao, Sichuan	Min River
1933.8.25	103°37'44.39"	32° 05'48.96"	Xiabailazhai	45 days	Mao, Sichuan	Min River
1935.11.25	102°16'24.95"	26°13'29.93"	Luchedu	3 days	Huidong, Sichuan	Jinsha River
1935.12.22	102°53'23.44"	26°56'38.61"	Shabagou	7 days	Qiaojia, Yunnan	Jinsha River
1934	104°06'36.24"	31°32'30.65"	Qingpingxiang		Mianzhu, Sichuan	Mianyuan River
1941.1.29	100°48′49"	36°05′38"	Chana	1 day	Gonghe, Qinghe	Yangtze River
1943	100°57′59.23"	36°07′45.99"	Longyang		Gonghe, Qinghai	Yellow River
1948.5.22	102°53′46.67"	30°16′46.42"	Xichuan		Xichuan, Sichuan	Wulian River
1951.7	98°18'50.89"	28°01'10.26"	Dongge	3-4 minutes	Gongshan, Yunnan	Nujiang River
1952.2	100°18'16.86"	30°34'40.69"	Jiaxi	3 days	Xinlong, Sichuan	Yalong River
1953.8	109°04′27.06"	34°12′02.49"	Jingyugou		Baqiao, Shanxi	
1959	97°28'15.39"	28°45'55.07"	Bagacun	7 days	Chayu, Tibet	Sangqu River
1962.8.15	110°26′35.70"	35°38′31.92"	Tianjiawa		Zizhou, Shanxi	
1963.1	102°23'27.31"	27°55'29.98"	Jisiamo		Xide, Sichuan	Dong River
1963.10.2	104°21'9.54"	33°46'53.75"	Bailongjiang		Zhouqu, Gansu	Bailong River

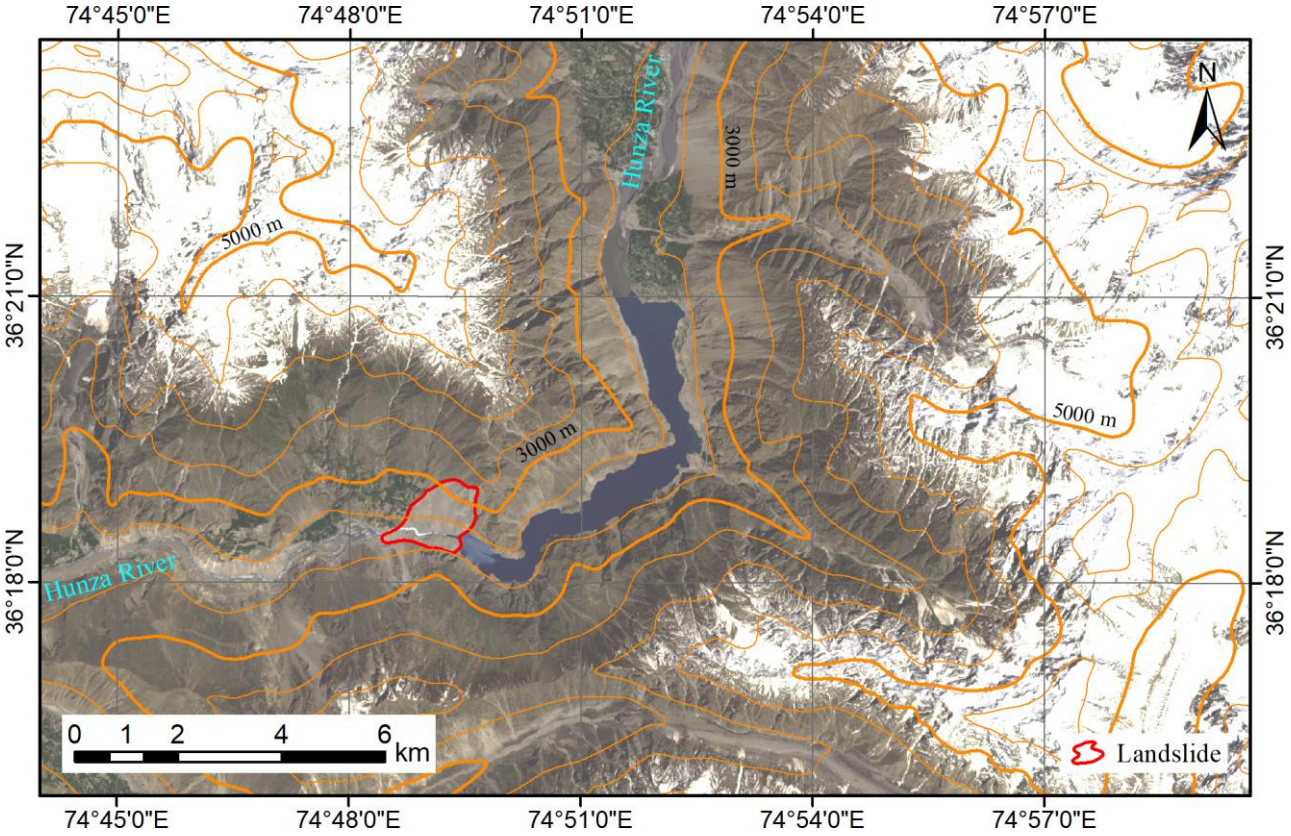
1964.7.20	103°36'04.03"	36°05'01.51"	Hongshuigou		Lanzhou, Gansu	Hongshui River
1965.7.7	105°39'40.99"	34°37'23.25"	Luoyugou		Tianshui, Gansu	Luoyu River
1965.11.20	102°38'45.89"	26°10'53.65"	Luquan	8 months	Qiaojia, Yunnan	Pufu River
1966	100°25'07.59"	26°47'42.98"	Jin'an		Lijiang, Yunnan	Jinsha River
1969.6.8	101°07'30.86"	29°24'33.92"	Tanggudong	9 days	Yajiang, Sichuan	Yalong River
1967.8.29	94°53'00.64"	29°59'55.98"	Layue		Linzhi, Tibet	Dongjiu River
1970.5.8	108°17′02.25"	28°18′18.42"	Xiapingxiangxintan		Dejiang, Guizhou	Wu River
1976	98°53'33.14"	27°14'56.05"	Lishadixiang		Fugong, Yunnan	Nujiang River
1976.7.25	104°32′09.06"	33°45′01.90"	Huamaxiang		Dangchang, Gansu	Bailong River
1979.5.25	103°13′49.26"	31°31′07.42"	Erpu		Li County, Sichuan	Zagunao River
1979.11.2	103°17'48.92"	29°53'02.51"	Luwanggou		Yaan, Sichuan	Qingyi River
1981.4.8	104°24'09.01"	33°44'56.25"	Xieliupo		Zhouqu, Gansu	Bailong River
1981.7.9	102°53'30.94"	29°12'55.71"	Liziyidagou	3 hours	Sichuan	Dadu River
1981.9.12	106°34'02.92"	33°14'58.79"	Wangjiagou		Mian County, Shanxi	Zhujia River
1982.7	104°32'35.61"	33°51'01.42"	Dengdengqiao		Dangchang, Gansu	Min River
1982.9.21	102°13'42.64"	29°56'25.80"	Hunshuigou		Luding, Sichuan	Anning River
1983.6.23	102°48'36.56"	26°58'50.64"	Baishuihegou		Puge, Sichuan	Baishui River
1983.7.2	98°10'27.78"	25°06'38.01"	Zhinaxiang		Dehong, Yunnan	Zhina River
1984.7	99°48'34.22"	24°20'52.76"	Libaluo	Brief	Fengqing, Yunnan	Yalan River
1984.7.18	103°44′32.63"	28°41′55.89"	Nanpingcun		Pingshan, Sichuan	Baihui River
1984.11.21	102°00'33.61"	35°31'01.43"	Nongwuxishan		Tongren, Qinghai	Longwu River
1985.6-7	103°12'06.98"	25°59'46.88"	Dabainigou	Brief	Dongchuan, Yunnan	Dabainigou River
1985.7	100°57′39.62"	22°51′29.66"	Changtian	2 years	Simao, Yunnan	Buyuan River
1985.8.21	98°26′36.71"	25°31′37.78"	Dapingshan	45 minutes	Baoshan, Yunnan	Nujiang River
1987	102°48'21.34"	29°02'47.31"	Leguluoduogou	Brief	Ganluo, Sichuan	Niuri River
1987.5.22	104°55'59.34"	33°27'26.89"	Beiyuhe		Wudu, Gansu	Beiyu River
1987.7.15	84°42′49.82"	43°43′46.50"	Kuitun2#	Few hours	Kuitun, Xinjiang	Kuitun River
1988	108°13'20.42"	32°00'01.49"	Diaobanya		Sichuan	Baisha River
1988.4.1	104°01'42.24"	31°25'12.84"	Yanziya		Shenfang, Sichuan	Zhong River
1989.3.15	103°18'32.89"	36°05'22.19"	Jiaojiayatou		Yongjing, Gansu	Yellow River
1989.7.26	102°04'50.59"	29°41'00.50"	Yanzigou	Brief	Luding, Sichuan	Dadu River
1990.5.31	102°17'30.76"	26°52'26.21"	Yimenkuang		Huili, Sichuan	Yimen River
1991.6	95°08'29.11"	30°04'13.70"	102 way		Bomi, Tibet	Palong Tsangpo River
1991.6.13	104°25'11.99"	33°43'09.99"	Nanyujiangdingya		Zhouqu, Gansu	Bailong River
1996.6.3	103°07'55.10"	22°51'56.57"	Laojinshan		Yuanyang, Yunnan	Jinzi River
1996.10.28	100°11'57.89"	27°17'56.58"	Huashiban		Lijiang, Yunnan	Jinsha River
1997.12.1	99°04'5.17"	29°25'34.97"	Suwalong		Batang, Sichuan	Jinsha River
1998.8.7	105°51'39.99"	28°01'18.17"	Gaozhiwan		Gulin, Sichuan	Gaozhiwan River
2000.4.9	94°56'22.68"	30°10'43.59"	Yigong	2 months	Bomi, Tibet	Yigong Tsangpo River
2004.6.22	78°42'34.66"	32°06'38.66"	Chulusongjie		Ali, Tibet	Pali River
2004.9.05	108°04'9.77"	31°25'45.94"	Tiantaixiang		Xuanhan, Sichuan	Qianzhi River
2005.8.24	101°59'17.46"	36°00'06.73"	Lannitan		Hualong, Qinghai	Yellow River
2008.5.12	105°07'14.50"	32°24'39.26"	Donghekou	Within 10 days	Qingchuan, Sichuan	Hongshi River

2008.5.12	103°50'50.34"	31°09'04.11"	Fengmingqiao	Within 10 days	Pengzhou, Sichuan	
2008.5.12	105°07'14.50"	32°24'39.26"	Hongshihe	Within 10 days	Qingchuan, Sichuan	Hongshi River
2008.5.12	104°45'33.29"	29°41'11.18"	Jiadanwan	Within 10 days	Neijiang, Sichuan	
2008.5.12	104°52'30.32"	32°13'56.81"	Jiaozigou	Within 10 days	Wenchuan, Sichuan	
2008.5.12	103°23'05.18"	30°49'20.26"	Liudinggou	Within 10 days	Chongzhou, Sichuan	
2008.5.12	104°53'09.45"	32°16'55.43"	Maanshi	Within 10 days	Dujiangyan, Sichuan	Zhenfu River
2008.5.12	103°59'45.12"	31°26'25.11"	Muguaping	Within 10 days	Deyang, Sichuan	
2008.5.12	103°58'33.36"	31°43'07.15"	Shibangou	Within 10 days	Qingchuan, Sichuan	
2008.5.12	104°08′23.28"	31°29′34.87"	Xiaogangjian	Within 10 days	Mianzhu, Sichuan	
2008.5.12	103°34'57.83"	30°55'52.40"	Yanziyan	Within 10 days	Dujiangyan, Sichuan	
2008.5.12	104°09′00.17"	31°29′21.79"	Yibadao	Within 10 days	Mianzhu, Sichuan	
2008.5.12	104°25'38.51"	31°50'42.05"	Tangjiashan	1 month	Beichuan, Sichuan	Qian River
2008.5.12	104°16′39.93"	31°38′53.77"	Xiaojiaqiao	24 days	An County, Sichuan	Chaping River
2014.8.3	103°23'56.07"	27°02'00.76"	Hongshiyan		Zhaotong, Yunnan	Niulan River
2017.6.24	103°38'48.51"	32°04'10.53"	Xinmocun		Mao County,Sichuan	Min River
2018.10.10	98°42′17.98"	31°04′56.41"	Baige	2 days	Baiyu, Sichuan	Jinsha River
2018.10.17	94°54′23.89"	29°42′22.49"	Milin	2 days	Milin, Tibet	Yarlung Tsangpo
2018.11.3	98°42′17.98"	31°04′56.41"	Baige	9 days	Baiyu, Sichuan	Jinsha River

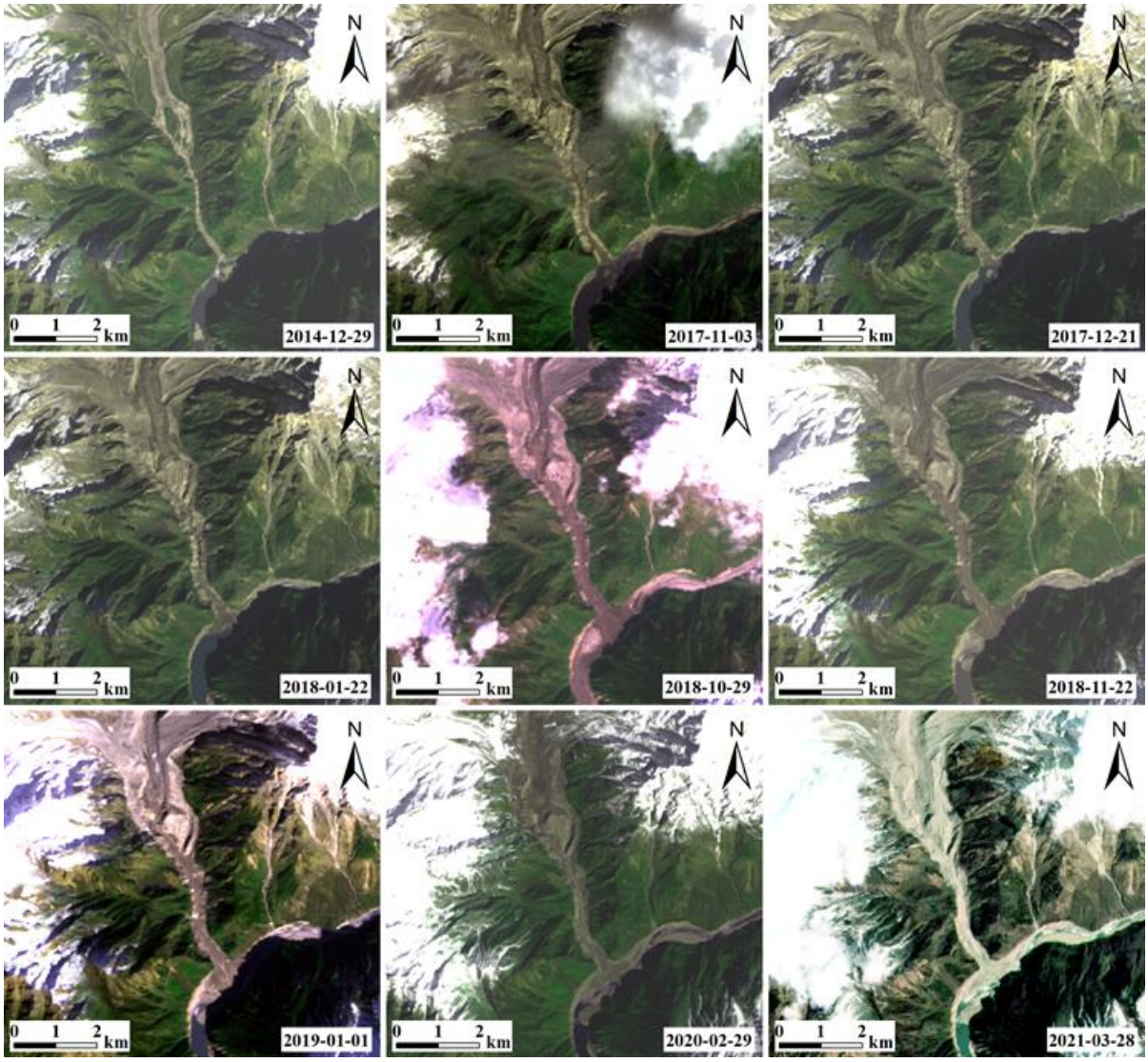
Supplementary Figures



Supplementary Fig. S1. Landforms associate with paraglacial adjustments and permafrost thaw slumps that have important implications for downstream hazards and sediment supplies. a, Landslides and debris cones after recent glacial retreats near Ranwu Lake, Bomi county, Tibet (Photo by D. Li). **b,** The proglacial lake of Bienong Tsho and adjacent slope failures, Jiali County, Tibet. Ice avalanche or landslide into moraine-dammed glacial lakes may trigger displacement waves and GLOFs (Photo by X. Sun). **c,** Unconsolidated moraine deposits exposed after the recent glacial retreat (a glacier along the Parlung River, Bomi County, Tibet), suggesting large amounts of materials (water-ice-sediment) available for potential debris flows (Photo by X. Sun). **d,** Large-scale thaw slumps in the central Tibetan Plateau (Photo courtesy of J. Chen).



Supplementary Fig. S2. The 2010 Attabad landslide-dammed lake on the Hunza River (Karakoram), upper Indus Basin, northern Pakistan (Sentinel-2; 05/2016). The Attabad landslide (45 million m^3) occurred this a periglacial environment in on January 4, 2010, destroyed over 20 houses and caused 20 deaths. The newly dammed barrier lake further ruined over 200 houses and severely affected the China-Pakistan Karakoram Highway (the world's highest highway)[16,17].



Supplementary Fig. S3. Multi-temporal comparison of satellite images of the Gyalha/Sedongpu LLOF (Landsat-8 images). Glacier detachments, rock-ice avalanches, and associated debris flows from the Sedongpu valley (near Gyalha Peri) have frequently blocked the mainstream of the Yarlung Tsangpo River since 2014. On 17/18 October 2018, a glacier detachment triggered debris flows that rapidly moved downstream and completely blocked the Yarlung Tsangpo River with a body of ice and debris with an estimated volume of 40-60 million m^3. The barrier lake breached naturally after two days resulting in a peak discharge of 32,000 m^3/s. Climate change, glacier retreat, antecedent earthquakes, steep topography, increased sediment availability and their interactions are reported to be responsible for the frequent hazards occurring in the Sedongpu valley[18–21].

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