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The Himalayas have experienced several glacial lake outburst floods (GLOFs), and the risk of GLOFs is now increasing in the context of global warming. Poiqu watershed in the Tibet Autonomous Region, China, also known as the Bhote Koshi and Sun Koshi downstream in Nepal, has been identified as highly prone to GLOFs. This study explored the distribution of and changes in glacial lakes, past GLOFs and the resulting losses, risk from potential future GLOFs, and risk reduction initiatives within the watershed. A relationship was established between lake area and volume of lake water based on data from 33 lakes surveyed within the Hindu Kush Himalayan region, and the maximum possible discharge was estimated using this and other previously developed empirical equations. We recommend different strategies to reduce GLOF risk and highlight the need for a glacial lake monitoring and early-warning system. We also recommend strong regional cooperation, especially on issues related to transboundary rivers.

Introduction

Glacial lake outburst floods (GLOFs), resulting from the sudden release of water from lakes impounded by moraine or ice dams, can be a major hazard in high mountain areas. Many moraine and ice dams are comparatively weak and can fail suddenly, resulting in the release of a debris-filled flood wave. Such flooding often results in injury and loss of life as well as serious damage to property and livelihoods far downstream (Hewitt 1982; Haeberli 1983; Ives 1986; Vuichard and Zimmermann 1987; Xu 1988; Ding and Liu 1992; Watanabe and Rothacher 1996; Dwivedi et al 2000; Richardson and Reynolds 2000; Carey et al 2012; NEC 2012; Khanal et al 2013; Liu et al 2013). The Hindu Kush–Himalayan (HKH) region has experienced many GLOF events over the years. At least 14 GLOF events have been reported that originated within Nepal (ICIMOD 2011), 30 in the Tibet Autonomous Region (TAR) in China (Liu et al 2013), and 21 in Bhutan and adjacent areas in the TAR (Komori et al 2012). GLOFs are becoming more frequent in the Pakistan Himalayas (Rehman et al 2013); there were 5 GLOFs in the Hunza basin of the Karakoram during 2007 and 2008, which severely affected nearby communities and pose a threat for the future (Ashraf et al 2012).

A small (statistically insignificant) increase in GLOF events in the Himalayas between 1940 and 2000 has been reported (Richardson and Reynolds 2000), but it is still not possible to determine whether there has been an increase in such events in recent years (Komori 2012). Observations in the Himalayas show a warming trend, increasing temperature extremes, and recession of mountain glaciers (Field et al 2012), and all projections for the 21st century show glaciers continuing to lose mass. Expansion or formation of lakes as a result of ice melt at the margins of receding glaciers increases the likelihood of GLOFs (Barros et al 2014; Field et al 2014). Climate change played a major role in the substantial increase in glacial lake area in the eastern Himalayas (Bhutan and Nepal) between 1990 and 2009 (Gardelle et al 2011), where the hazard from moraine- and ice-dammed lakes continues to increase (Field et al 2014).

The Poiqu watershed in TAR, China, is highly prone to GLOFs. The Poiqu River extends into Nepal, where it is known as the Bhote Koshi as far south as Barhabise and then as the Sun Koshi. Five GLOF events have been reported in this watershed since 1935. Wheat fields were damaged and several yaks were swept away by a GLOF from Taraco glacial lake on 28 August 1935 (LIGG et al 1988). Two GLOF events have been reported from Zhangzambu (Ci-Ren-Ma-Co) glacial lake, 1 in 1964 and 1 in 1981 (LIGG et al 1988; Xu 1988). The latter resulted in

the destruction of Quxiang village and a highway bridge in China and damage to 47 houses, 12 bridges, 27 km of road, 1 of the gates in the Sun Koshi hydropower dam, and a transmission line in Nepal. In Nepal, 5 people were swept away, the power supply was cut for 31 days, traffic was blocked and trade disrupted for 36 days, and transport services were affected for 3 years; total losses were estimated to be close to US\$ 4 million (Khanal and Acharya 2008). The maximum discharge in the 1981 GLOF was estimated to be 15,920 m^3/s 23 minutes after bursting. The flood lasted for 60 minutes, and the total outflow was 19 million m^3 (Xu 1988). The peak discharge of 2316 m^3/s (gauge height of 6.99 m) at Barhabise about 50 km downstream was 16 times greater than the average annual flood (maximum flow). The flood carried nearly 4 million m^3 of mixed debris; the debris flow dammed the Poiqu River, and the water level rose to 30 m, destroying Quxiang village, located upstream of the confluence between the Zhangzambu tributary and Poiqu River (Xu 1988). Two GLOF events were also reported from Jia-Long-Co glacial lake in 2002. The event on 29 June 2002 destroyed bridges and resulted in an estimated economic loss of 3.05 million yuan renminbi (approximately US\$ 370,000) (Chen et al 2013).

The glaciers in the Poiqu watershed are shrinking, and their retreat has been accelerating since 2000 (Xiang et al 2014). The rapid expansion of glacier-fed lakes has increased the risk of GLOFs (Chen, Cui, Li, et al 2007; Xiang et al 2014; Wang et al 2015). In this article, we discuss the GLOF risk in the transboundary watershed and propose management strategies.

Study area

The Poiqu/Bhote Koshi/Sun Koshi is a transboundary river that originates in TAR in China and flows across the high mountain region into Nepal and then India. The study site (27°20′–28°40′N latitude, 85°40′–86°20′E longitude) comprises the Poiqu watershed in China and the Bhote Koshi/Sun Koshi watershed to Dolalghat in Nepal (Figure 1). The elevation ranges from 649 m above sea level at Dolalghat to more than 8000 m above sea level in China. The total watershed area is about 3393 km^2 with a river length of 146 km, about 78 km in China and 68 km in Nepal. Annual mean precipitation ranges from more than 1100 mm in the southern part to less than 700 mm in the north.

International trade and tourism between Nepal and China have been growing rapidly since the opening of the Kodari Highway along the Poiqu/Bhote Koshi/Sun Koshi valley, which links Kathmandu, the capital of Nepal, with Khasa (Zhang-Mu) in TAR, China. The records of the Customs Office in Nepal show a value of US\$ 135.9 million in imports and US\$ 4.1 million in exports in 2011/2012, with both governments benefiting from the revenue. Nearly 69,000 tourists cross the border annually.

Four hydroelectricity projects are in operation, and many more are planned.

Approximately 200,000 people live in the watershed, only 2.7% of whom live in China. Agriculture is still the major source of family income. In Nepal, remittances, wage labor, portering, and services also contribute to family income; trade and business contribute in both Nepal and China. The other major economic activities in the watershed are international trade, tourism, and hydroelectricity production.

In 2010 a total of 124 glaciers were mapped in TAR, China, with an area of 203.4 ± 5.3 km^2 (Xiang et al 2014). Both the number and the area of glaciers have decreased, with large glaciers shrinking and smaller glaciers retreating at a faster rate (Xiang et al 2014). The average monthly temperature in the watershed is projected to increase under A1B, B1, and A2 climate-change scenarios (CDG and AIRC 2013). The winter temperature is likely to increase at a higher rate. The increase in temperature will cause more glacier ice to melt, potentially leading to higher-magnitude GLOFs (CDG and AIRC 2013).

Methods

Four main processes are considered in GLOF risk management: hazard identification, hazard estimation, risk evaluation, and risk reduction (Reynolds Geo-Sciences 2003; Huggel 2004; Carter et al 2007). This study looked at each of these in the following steps: (1) identification of potentially dangerous glacial lakes, (2) estimation of the volume of water in each lake and potential magnitude of flooding, (3) identification and quantification of past losses and elements exposed to future GLOF risk, and (4) identification of risk reduction strategies.

Identification of potentially dangerous lakes

Various authors have attempted to develop ways to estimate the qualitative or relative probability of a GLOF (Huggel, Haeberli et al 2004; Wu et al 2005; McKillop and Clague 2006; Wang et al 2009; ICIMOD 2011; Mergilli and Schneider 2011; Wang et al 2011; Worni et al 2013; Che et al 2014; Wang et al 2015). The main parameters used to identify potentially dangerous glacial lakes are dam type, ratio of freeboard to dam height, ratio of dam width to height, likelihood of impact waves from ice or rock falls into the lake, likelihood of extreme meteorological events, presence or absence of an ice core in the moraine, lake area, lake drainage area, lake area development, lake volume, mother glacier area, distance between the lake and glacier terminus, and slope between the lake and glacier terminus.

This study selected several indices easily obtained through field survey and interpretation of remote sensing images to identify potentially dangerous lakes. They included the type of lake (moraine-dammed,

FIGURE 1 Location of study area. (Map by authors)
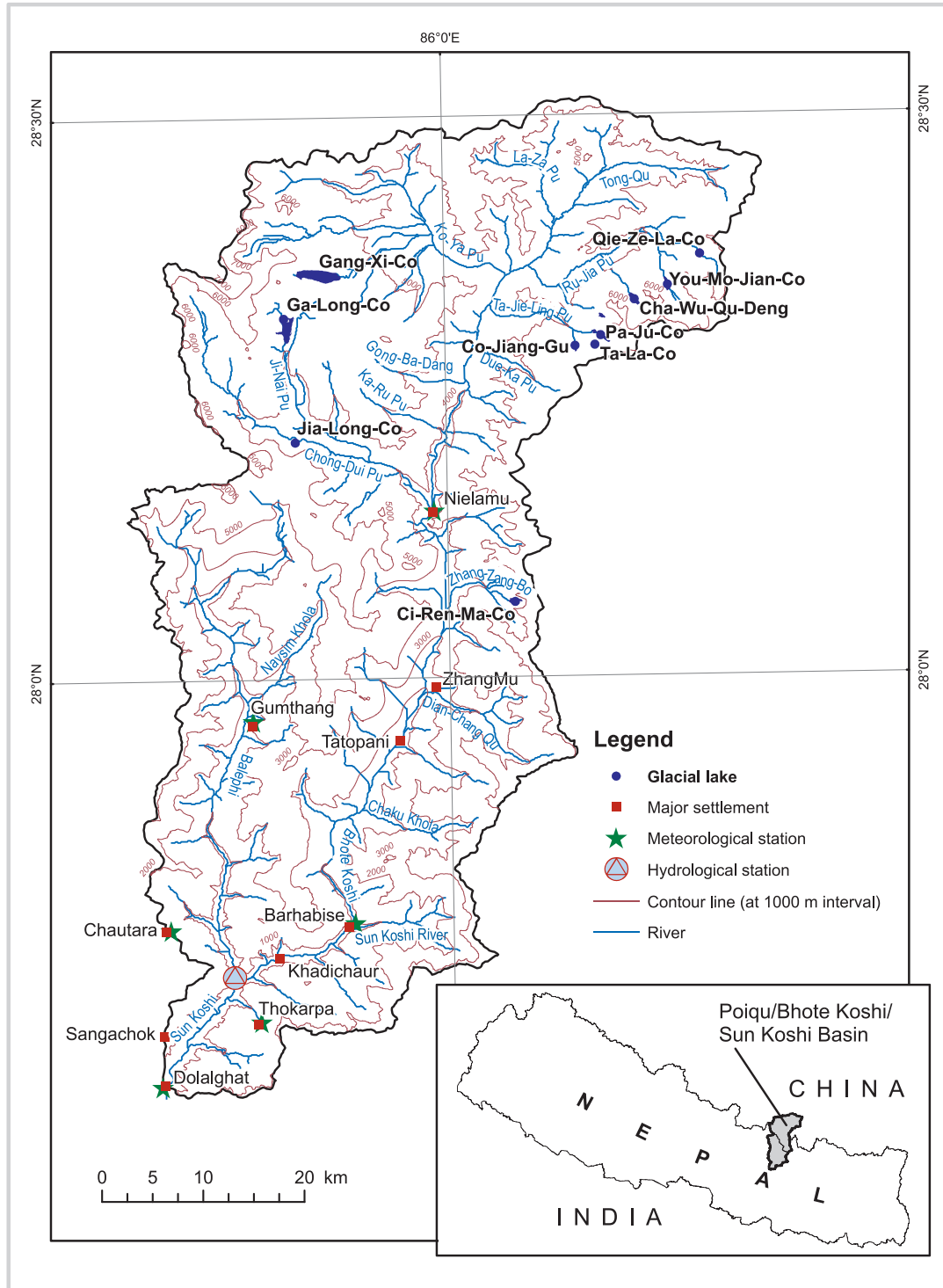
glacier erosion, or other), dam texture (consolidated or unconsolidated, bedrock, or other), outlet position (channel on the dam surface, drainage underneath the dam, or no outlet), presence and size of any mother glacier, distance from mother glacier to lake,

and the lake's current area and changes in area over time.

An inventory of all the glacial lakes in the watershed in 2012 was prepared using Landsat ETM+ images (22 October 2012). Glacial lakes with an area greater than 0.1

km^2 were selected for field survey using Google Earth maps. Detailed information for these lakes was obtained during a field survey in September and October 2012 (Table 1). The area of the 21 largest of these lakes was also derived from Landsat images (30 November 1991 and 11 October 2002) to give values for 1991, 2002, and 2012 for trend analysis. Past GLOF events were identified through literature review and interviews with the local community.

The information derived from the investigations was used to determine potentially dangerous lakes based on criteria such as whether or not a GLOF had already been recorded, the characteristics of the lake (eg size and growth rate) and glacier (eg speed of retreat), and the condition of the dam (eg stability) and surroundings (Table 1). Details of the basic approach are provided in ICIMOD (2011). Four levels were differentiated: outburst plus very critical, very critical, critical, and stable. For example, a glacial lake dammed by an unconsolidated mixed moraine with a very large mother glacier was identified as very critical, a glacier lake dammed by a mixed moraine with a small mother glacier was considered critical, and a glacier erosion lake with a bedrock bank was considered stable.

Estimation of the volume of water in a lake and potential magnitude of flooding

Lake volume and maximum possible discharge, important factors in GLOF risk level, were estimated based on 7 empirical equations (Table 2), 6 developed by others (Huggel et al 2002; Huggel 2004; Huggel, Haeberli, et al 2004; Huggel, Kääb, and Salzmann 2004; McKillop and Clague 2006; Wang et al 2008) and 1 developed for this study. The new equation (equation 3 in Table 2) was derived from regression analysis of a plot of published data on volume and area of 33 Himalayan glacial lakes measured in the field by various authors (for details see *Supplemental material,* Table S1 (http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00009. S1). The trend line has an R^2 value of 0.94, indicating a good fit (Figure 2).

Volume and maximum possible discharge were estimated for the 10 critical lakes using these empirical equations and the lake areas derived from remote sensing images.

Identification and quantification of past losses and potential future losses

Information on past GLOF events and associated losses and elements exposed to a potential GLOF in the downstream area in Nepal were collected along the Bhote Koshi/Sun Koshi River through discussions with local people and key informants. Similar information for the upstream area in TAR, China, was collected through observation by the research team, discussion with key

informants, and review of published articles. Fieldwork was carried out during 2008, 2012, and 2014.

Two flood scenarios were used to assess the potential GLOF risk in downstream areas in Nepal. The first was the flood level experienced during the disastrous flood in 1981. Local people were asked to mark the 1981 flood level at different places; these were noted on a topographical map and linked by contours to delineate the total area affected. The second scenario was a flood level 10 m higher than the 1981 level, and the area that would be affected was again delineated on a topographical map. Local people were then asked to describe in detail the elements that would be exposed in the areas affected under the scenarios, including people, property, infrastructure, livestock, elements that contribute to livelihoods such as tourism and trade, and environmental resources such as forest, grassland, and fisheries.

For the purpose of data collection, the Bhote Koshi/Sun Koshi River was divided into 10 blocks between Dolalghat in the south and the Nepal-China Friendship Bridge in the north, incorporating at least 1 major settlement in each block. At least 1 meeting was held with 8 to 12 key informants in each block. Community-based interactive GLOF hazard mapping was carried out with direct field observation along the river. In addition, interviews were conducted with wholesale agents, personnel of the Tatopani customs office at the Nepal–China border, and local traders to collect information on trade and traffic flow and associated employment and livelihoods.

A structured checklist was prepared to record information on different aspects necessary for vulnerability and risk assessment: (1) GLOF and other flash flood hazards and losses in the past; (2) people, houses, land, crops, biodiversity, infrastructure, and other elements exposed to potential hazards; (3) flow of vehicles, people, goods, and services; and (4) information related to vulnerability and adaptive capacity—such as ethnicity, family type, level of education, landholding size, livelihood options, annual income, food sufficiency, social networks and institutions, indigenous knowledge, preparedness and mitigation strategies and activities, and expected mitigation measures and adaptation strategies for GLOF risk management.

A cost-per-unit approach was used to estimate potential loss in monetary terms. The value of individual property was calculated and summed to give a figure for total potential loss. Prevailing local purchase values were used for household assets (houses, land, crops, and livestock) and replacement costs for infrastructure (buildings, roads, trails, bridges, hydropower and water supplies, and communication cables). National average per-unit cost was used to estimate the replacement cost of infrastructure (except private houses). Revenue from

TABLE 1 Information on selected glacier lakes obtained by field survey. (Continued next page.)

Lake	Type	Dam texture	Dam outlet position	Mother glacier	Distance from mother glacier to water surface
Jia-Long-Co	Moraine dammed	Consolidated mixture (small boulders, gravels, coarse sands)	Channel on surface	Large hanging glacier	<100 m horizontally about 500 m vertically
Ci-Ren-Ma-Co south (Zhangzangbo)[a]	Moraine dammed	Unconsolidated mixture (big boulders, gravels, coarse sands)	Channel on surface	Not surveyed	Not surveyed
Co-Jiang-Gu	Moraine dammed	Unconsolidated mixture (big boulders, gravels, coarse sands)	Channel on surface and drainage from underneath	Large hanging glacier	<600 m horizontally <200 m vertically
You-Mo-Jian-Co	Moraine dammed	Unconsolidated mixture (boulders, gravels, coarse sands)	Channel on surface	Large glacier	Adjacent/in contact
Qie-Ze-La-Co	Moraine dammed	Unconsolidated mixture (boulders, gravels, coarse sands)	Drainage from underneath	Large trough glacier	Adjacent/in contact
Ta-La-Co	Moraine dammed	Unconsolidated mixture (boulders, gravels, coarse sands)	Channel on surface and drainage from underneath	Large glacier	<300 m horizontally <100 m vertically
Ga-Long-Co	Moraine dammed	Unconsolidated mixture (big boulders, gravels, coarse sands)	Drainage from underneath	Large glacier	Adjacent/in contact
Gang-Xi-Co	Moraine dammed	Unconsolidated mixture (big boulders, gravels, coarse sands)	Drainage from underneath	Large glacier	Adjacent/in contact
Pa-Ju-Co	Moraine dammed	Consolidated mixture (boulders, gravels, coarse sands)	Channel on surface	Large glacier	<400 m horizontally <200 m vertically
Cha-Wu-Qu-Deng	Moraine dammed	Unconsolidated mixture (boulders, gravels, coarse sands)	Channel on surface and drainage from underneath	Large hanging glacier	<200 m horizontally <100 m vertically
Gong-Co	Glacier erosion	Consolidated mixture (boulders, gravels, coarse sands) with underlying bedrock	No outlet	Small glacier	>1000 m horizontally >1000 m vertically
Ta-Ro-Co	Glacier erosion	Consolidated mixture (boulders, gravels, coarse sands) with underlying bedrock	No outlet	Large glacier	Not clear

TABLE 1 Continued. (First part of Table on previous page.)

Lake	Type	Dam texture	Dam outlet position	Mother glacier	Distance from mother glacier to water surface
Ga-Long-Co southwest	Moraine dammed	Unconsolidated mixture (boulders, gravels, coarse sands)	Channel on surface	No glacier	Not applicable
Co-Na-Nang-Song	Moraine dammed	Consolidated mixture (boulders, gravels, coarse sands)	Channel on surface	Small glacier	Not clear

a) Not surveyed; information is based on previous observations.

international trade and supply of electricity were also taken into account.

The estimates did not include potential loss of internal household property such as jewelry and ornaments, furniture, radios, televisions, and vehicles. It was also not possible to incorporate the potential indirect tangible losses such as to communication, health care and education, utility supplies, income, emergency services, and mitigation activities.

Identification of risk reduction strategies
Information on GLOF risk management initiatives at local and national levels was also collected during the discussions. Following the identification of potentially dangerous lakes, appropriate sites for discharge monitoring and early warning were identified, keeping in view both the need to maximize lead time and the location of major settlements and market towns.

Results

Glacial lakes
A total of 74 glacial lakes were identified and mapped in the watershed, based on Landsat ETM+ (22 October 2012) (see *Supplemental material,* Table S2; http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00009.S1). Of the 74 lakes identified, 65% were very small (area < 0.10 km^2), 12% were small (area 0.10–0.25 km^2), 19% were large (area 0.25–1.00 km^2), and 4% were very large (area > 1.00 km^2). Table 3 shows the 21 larger lakes selected for closer study, their area in 1991, 2002, and 2012, and their estimated level of GLOF risk. Almost all the lakes showed an increase in area. Three (Qie-Ze-La-Co, Ga-Long-Co, and Co-Na-Nang-Song) more than doubled in area, and 7 grew by 50–100%. After analyzing the characteristics of the lakes, glaciers, dams, and surroundings, 10 lakes were identified as having a critical potential for a GLOF event. Of these, 6 were identified as very critical.

Water volume and discharge
Table 4 shows the volume of water and maximum possible discharge from the 10 critical lakes estimated using the empirical equations shown in Table 2.

Risk of glacial lake outburst flood
The level of GLOF hazard along the various rivers in the watershed was assessed using the glacial lake hazard as a base. The level of hazard along the Chong-Dui Pu, Ji-Nai Pu, Ko-Ya Pu, Ru-Jia Pu, Ta-Jie-Ling Pu, and Zhang-Zang-Bo Rivers (Figure 1) is high or very high as the glacial lakes that feed into these rivers have a high potential of breaching. The gradient of the upper part of the Poiqu River is relatively low, and it is further from Nepal; thus, the risk of a GLOF along the Ko-Ya Pu, Ru-Jia Pu, and Ta-Jie-Ling Pu Rivers would remain within these valleys, whereas a GLOF along the Chong-Dui Pu, Ji-Nai Pu, and Zhang-Zang-Bo Rivers could have a much greater impact downstream.

Elements exposed to a potential glacial lake outburst flood
There are 17 settlements with around 5000 people, 21 bridges, and 1 hydropower plant in the valleys in the upstream area in China that could be affected by a GLOF. Of these, 2 settlements (Ou-Re and Ru-Jia), 4 bridges, and 1 hydropower plant are close to the rivers and likely to be at risk, but detailed modeling could not be carried out to determine the precise risk level.

In the downstream area to Dolalghat in Nepal, modeling showed that a GLOF at a level 10 m above the level in 1981 along the Bhote Koshi/Sun Koshi River would potentially affect approximately 3000 households with 16,000 people, 170 ha of cultivated land, 1500 t of agricultural crops, 2000 houses, 30 public buildings, 37 km of roads, 21 km of trails, 7 road bridges, 23 suspension footbridges, 3 hydropower projects, 11 water mills, 25 km of transmission line, 8 km of drinking water pipeline, and 9 km of communication cable.

The total estimated value of property exposed to potential risk from a GLOF in the Nepal part of the watershed ranged from US$ 153 million (for a GLOF of the same magnitude as in 1981) to US$ 189 million (for a GLOF 10 m higher than 1981), which is very high compared to the estimated losses during the 1981 GLOF. The higher value is partly due to the fact that a considerable amount of infrastructure—including hydropower plants, communication cables, bridges, public buildings, and private houses—has been developed

TABLE 2 Empirical equations used for estimating lake volume and maximum possible discharge.

|	Equation[a]	References
Lake volume	$V = 0.104A^{1.42}$ (1)	Huggel et al 2002 ; Huggel, Haeberli et al 2004
	$V = 0.035A^{1.5}$ (2)	Evans 1986; Huggel et al 2002
	$V = 0.0578A^{1.4683}$ (3)	Trend line derived from data for area and volume of 33 glacial lakes in the HKH region (see Figure 2 and Table S1)
Maximum possible discharge	$Q_{max} = 0.00077V^{1.017}$ (4)	Huggel et al 2002
	$Q_{max} = 0.0048V^{0.896}$ (5)	Popov 1991 (cited in Huggel et al 2002; Wang et al 2008)
	$Q_{max} = 0.72V^{0.53}$ (6)	Evans 1986 (cited in Huggel et al 2002; Wang et al 2008)
	$Q_{max} = 0.045V^{0.66}$ (7)	Walder and O'Connor 1997 (cited in Wang et al 2008)

[a] V = volume in m^3; A = area in m^2.

since 1981, and partly to the fact that the estimated loss in 1981 was based on actual loss, which is less than potential loss. Infrastructure comprised about 65% of the total value exposed to a GLOF at the 1981 level, followed by government revenue (10%) and real estate (private buildings and cultivated land). Figure 3 shows the value of the elements exposed along the different reaches of the river. The value was higher at locations with expensive infrastructure and more developed markets.

GLOF risk reduction initiatives

The need to work on GLOF risk management was recognized at both national and local levels after the devastating GLOF event of 1981. In Nepal, the National Strategies for Disaster Risk Management (2009), National Adaptation Program of Action (2010), and Climate Change Policy (2011) and in China the National Adaptation Strategies for Climate Change and National Disaster Reduction Plan (2006–2010) emphasized and

FIGURE 2 Relationship between glacial lake volume and area for 33 Himalayan lakes. (Sources provided in *Supplemental material,* Table S1 (http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00009.S1)
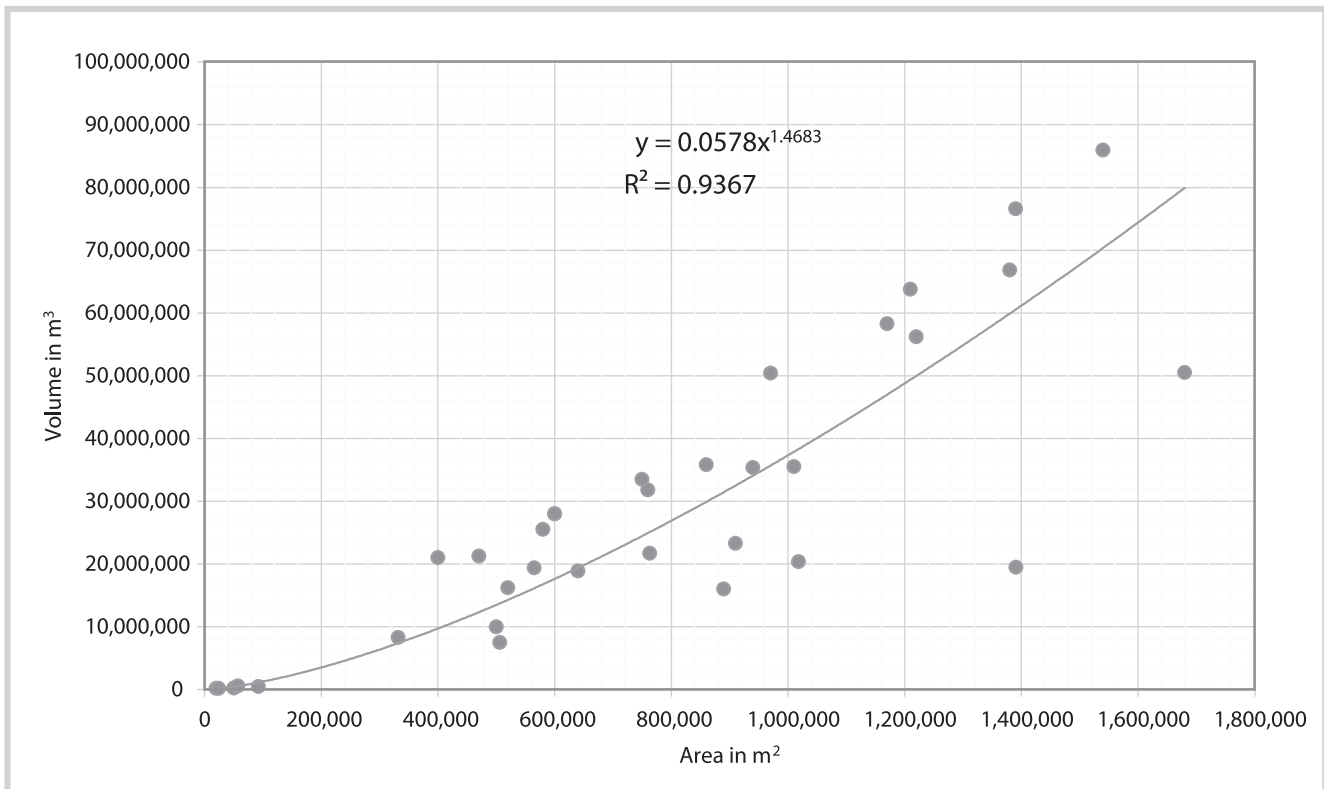
TABLE 3 Area of selected glacial lakes, 1991–2012, and their level of outburst flood risk.

Lake	Risk of outburst	Area (km^2)			% change 1991–2012
		1991	2002	2012	
Jia-Long-Co[a]	Outburst in the past + very critical	CC	IC	0.552	– [d]
Ci-Ren-Ma-Co south (Zhangzangbo)	Outburst in the past + very critical	0.312	0.471	0.477	53
Co-Jiang-Gu[a]	Outburst in the past + very critical	0.204	0.236	0.376	84
You-Mo-Jian-Co[a]	Very critical	0.347	0.335	0.546	57
Qie-Ze-La-Co[a]	Very critical	0.133	0.180	0.349	162
Ta-La-Co[a]	Very critical	0.151	0.171	0.239	58
Ga-Long-Co[a]	Critical	2.372	2.577	5.289	123
Gang-Xi-Co[a]	Critical	2.785	3.602	5.283	90
Pa-Ju-Co[a]	Critical	0.608	0.627	0.873	44
Cha-Wu-Qu-Deng[a]	Critical	0.675	0.601	0.679	<1
Gong-Co[a,b]	Stable	0.851	1.406	2.273	–[d]
Ta-Ro-Co[a]	Stable	0.540	CC	0.543	<1
Yin-Ra-Co	Stable	0.315	0.344	0.341	8
Ga-Long-Co southwest[a]	Stable	0.258	0.326	0.321	24
Co-Na-Nang-Song[a]	Stable	0.122	0.178	0.312	156
Xia-Hu[c]	Not yet studied	Small	0.320	0.419	– [d]
Gang-Pu-Co	Not yet studied	0.178	0.233	0.309	74
Co-Nong-Jue	Not yet studied	0.295	0.281	0.288	−2
Duo-Ka-Pu-Co	Not yet studied	0.159	0.143	0.198	25
Ma-Bi-Ya	Not yet studied	0.091	0.141	0.155	70
Mu-La-Co	Not yet studied	0.114	0.113	0.119	4

[a]Lake was surveyed for this study.

[b]Lake was covered by ice in 1991; area was larger than shown here.

[c]Very small for mapping. Dates of measurement: 30 November 1991, 11 October 2002, 22 October 2012.

[d]The percentage change is given by "for those lakes for which the area for the base year was not determined accurately due to either cloud cover or ice cover, or was too small for mapping."

prioritized flood risk management. Sino-Nepalese investigation of glacial lakes and GLOFs in the Poiqu/Bhote Koshi/Sun Koshi watershed, including the Pumqu (Arun) basin, was started in April 1987 with contributions from Canadian scientists, and a report was published in 1988 (LIGG et al 1988). The joint expedition team of experts recommended monitoring of glacial lakes and establishment of an early-warning system in the source area.

During the rehabilitation work following the 1981 GLOF, the road was realigned in several places to a higher altitude and away from the flood plain, and arch-type bridges were introduced in place of truss bridges at Phupling and Zhangzambu. The Bhote Koshi

hydroelectricity project has installed an early-warning system with 5 sensors near the Nepal-China Friendship Bridge with automatic sirens at 4 locations. The system is tested every 3 months and is fully functional. People living in the locality have been trained by the project, and signboards about the siren system have been placed at many sites within the project area. However, there is no monitoring and early-warning system downstream from the powerhouse, and the lead time of 6 minutes between the flood sensor and the powerhouse is too short for real action.

This study identified sites that would be appropriate for the installation of a monitoring and early-warning system to manage some of the risk from a potential GLOF

TABLE 4 Estimated volume of water and maximum possible discharge for critical glacial lakes, 2012.[a]

Lake	Volume (m³)			Possible discharge (m³/s)	
	Equation 1	Equation 2	Equation 3	Minimum	Maximum
Jia-Long-Co	14,816,799	14,359,974	15,595,175	2382	15,913
Ci-Ren-Ma-Co (Zhangzangbo)	12,053,438	11,546,753	12,597,886	2063	12,808
Co-Jiang-Gu	8,578,076	8,061,512	8,862,414	1627	8957
You-Mo-Jian-Co	14,577,312	14,114,907	15,334,605	2355	15,643
Qie-Ze-La-Co	7,716,201	7,208,408	7,943,309	1511	8013
Ta-La-Co	4,522,615	4,099,721	4,571,891	1041	4569
Ga-Long-Co (Phu Chhu, Lumichimi)	366,611,694	425,706,145	430,367,197	20,211	464,628
Gang-Xi-Co	365,991,732	424,945,729	429,614,687	20,188	463,802
Pa-Ju-Co	28,376,289	28,526,831	30,534,462	3734	31,515
Cha-Wu-Qu-Deng	19,876,222	19,584,869	21,130,471	2923	21,673

[a] Range of possible discharge is based on calculations using equations 4, 5, 6, and 7; all minimum values were calculated using equation 7, and all maximum values using equation 4.

in the watershed (Figure 4). These sites are recommendations. Six sites were identified where a monitoring system could be installed to observe the discharge from (and water level of) the 10 critical glacial lakes (Table 3). Of these, 4 (MS1, MS2, MS3, and MS6) are located near single lakes (Jia-Long-Co, Ga-Long-Co, Gang-Xi-Co, and Ci-Ren-Ma-Co) to observe both water level and discharge, and 2 (MS4 and MS5) are located downstream of a group of lakes to observe discharge (on the Ru-Jia River to observe discharge from You-Mo-Jian-Co, Qie-Ze-La-Co, and Cha-Wu-Qu-Deng lakes, and on the Ta-Jie-Lin River to observe discharge from Co-Jiang-Gu, Ta-La-Co, and Pa-Ju-Co lakes). It is recommended that the monitoring systems transmit information by wireless technology in real time to a management center staffed with (or linked to) experts who can judge whether the discharge or water level is abnormally high and indicative of an increased GLOF risk. Warning messages would be sent via multiple media to downstream communities and managers of important infrastructure (hydropower plants, trade centers, and bridges) through the early-warning system. About 20 sites associated with downstream communities and infrastructure were identified for installation of early-warning systems (Figure 4).

Discussion

All 21 lakes selected for study over time increased in area between 1991 and 2012 (Table 3). Previous studies have also shown an increase in both number and area of glacial lakes in the watershed. The number of lakes with an area of more than 0.02 km² increased by 11% and the total area by 47% between 1986 and 2001; the total area

increased by 83% over the 35 years from 1976 to 2010 (Wang et al 2015). The area of large glacial lakes such as Ga-Long-Co, Gang-Xi-Co, and Ci-Ren-Ma-Co increased by more than 100% over the same period (Chen, Cui, Yang, and Qi 2007).

Four of the lakes identified as critical in the present study (Jia-Long-Co, Ci-Ren-Ma-Co, Ga-Long-Co, and Cha-Wu-Qu-Deng) were also identified as potentially dangerous by Chen, Cui, Yang, and Qi (2007), and 3 (Ci-Ren-Ma-Co, Ga-Long-Co, and Gang-Xi-Co) by Wang et al (2015).

The lake volume estimated using the new equation derived from 33 glacial lakes in the HKH region (equation 3) was higher than the volume estimated using the previously published empirical equations (Table 2). The original author has already reported that using equation 1 to estimate the volume of large Himalayan glacial lakes results in underestimation by 16–80% (Huggel, Haeberli, et al 2004). However, field measurement is needed to confirm whether equation 3 results in over- or underestimation.

The range of possible peak discharge estimated using the 4 published empirical equations is very large. Some indication of the extent to which the estimates reflect the real situation can be gathered from field measurements and modeling experiments carried out for 2 lakes. The maximum possible discharge from Ci-Ren-Ma-Co (Zhangzambu Lake), the lake that gave rise to the GLOF in 1981, estimated using the empirical equations, ranged from 2000 to 13,000 m³/s. The peak discharge estimated from field measurement of channel geometry and water level (taking into account the contribution of sediment to water level) after the GLOF of 1981 was 15,920 m³/s (Xu 1988), and the simulated discharge estimated using the

FIGURE 3   Estimated monetary value of elements exposed to a potential GLOF risk in different reaches of the Bhote Koshi/Sun Koshi watershed in Nepal. (A) At the same flood level as the 1981 GLOF; (B) at a level 10 m higher. Area of disk indicates total value. (Based on Khanal and Acharya 2008)
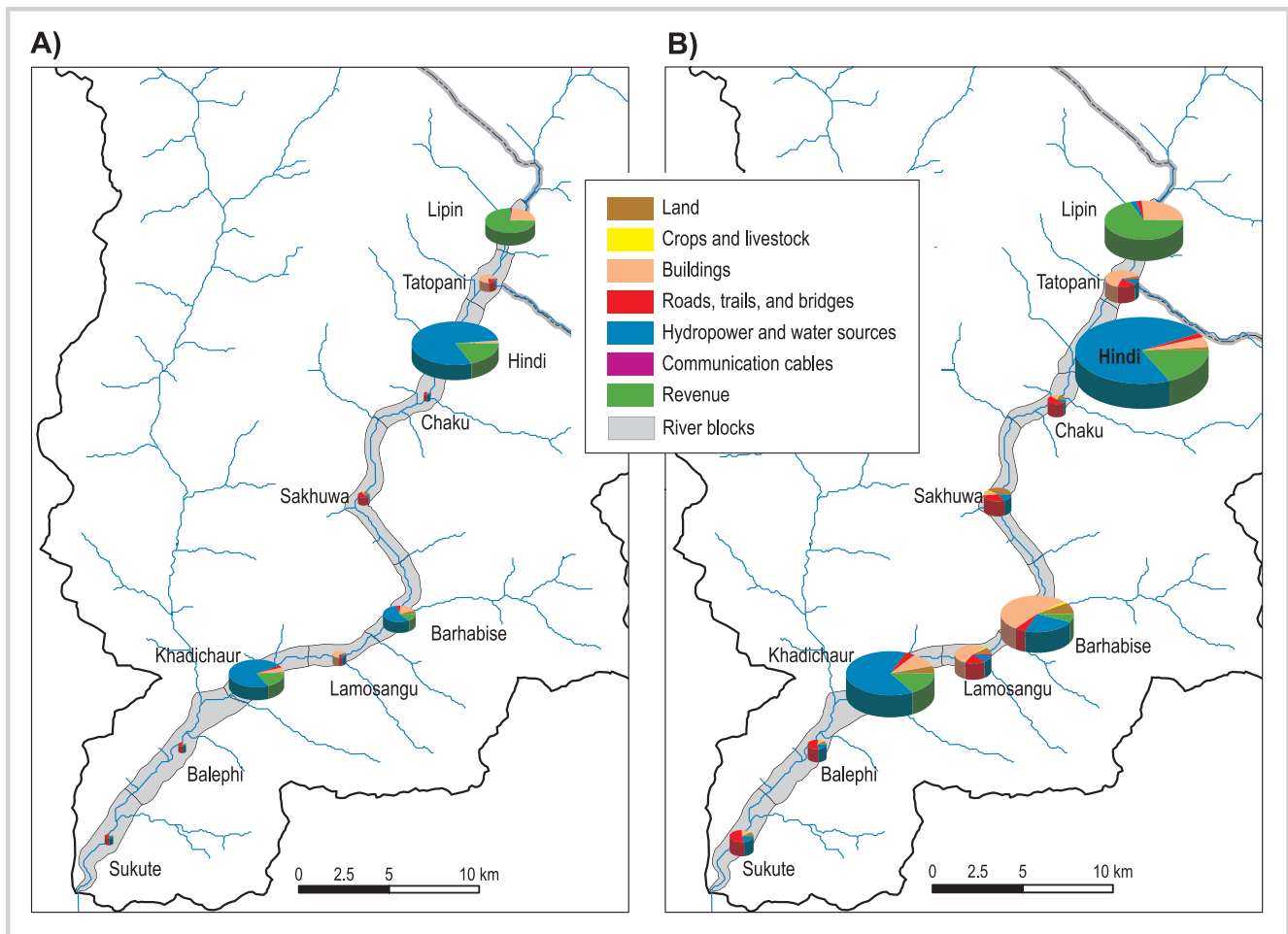

Simplified Dam-Break (SMPDBK) model was 2846 m^3/s (WECS 1987). The range of estimates made using the empirical equations lies between these 2 values. Similarly, the maximum possible discharge from Ga-Long-Co estimated using the empirical equations ranged from 20,000 to 465,000 m^3/s. The peak discharge estimated by WECS in 1987 from modeling of the same lake (called Phu Chhu in that study) was 31,724 m^3/s (WECS 1987), while other modeling estimates for the same lake (also called Lumuchimi) were between 5040 and 12,286 m^3/s (Shrestha et al 2010; Ghimire and Misra 2013), somewhat less than the discharge modeled by WECS, and much less than the maximum possible discharge estimated using the empirical equations.

It seems likely that the empirical equations overestimate the peak discharge, especially in bigger lakes such as Ga-Long-Co and Gan-Xi-Co (Table 4), but it is still difficult to ascertain which of the empirical equations gives the best estimates. Nevertheless, the estimated peak discharge does provide a basis for estimating the relative risk from the critical lakes, although improved equations are needed for quantifying this risk.

The estimated total value of property exposed to a potential GLOF risk of US\$ 153–189 million (in Nepal) is less than the estimate for Thulagi glacial lake on the Marsyangdi River in western Nepal and higher than the estimate for Imja and Tsho Rolpa glacial lakes in eastern Nepal (Khanal et al 2015). The total monetary value at risk depends largely on the level of development of infrastructure along the river valley. In the Bhote Koshi watershed, revenues from international trade and supply of hydropower are among the highest-value elements exposed to potential GLOF risk and are likely to increase as trade volume increases and new hydropower projects are developed.

A number of GLOF risk reduction strategies have been initiated at the national level, but activities have not yet been developed and implemented at the watershed level. The Poiqu/Bhote Koshi/Sun Koshi is a transboundary river, with all the glacial lakes that are a potential GLOF hazard located in China, while most of the people and properties exposed to the risk lie downstream in Nepal. Thus, strong bilateral cooperation is needed between the 2 countries to develop and implement effective GLOF risk reduction activities at the watershed level. The current

FIGURE 4 Location of sites recommended for the installation of discharge and water level monitoring and early-warning systems in the Bhote Koshi/ Sun Khoshi watershed. (Based on Khanal et al 2014)
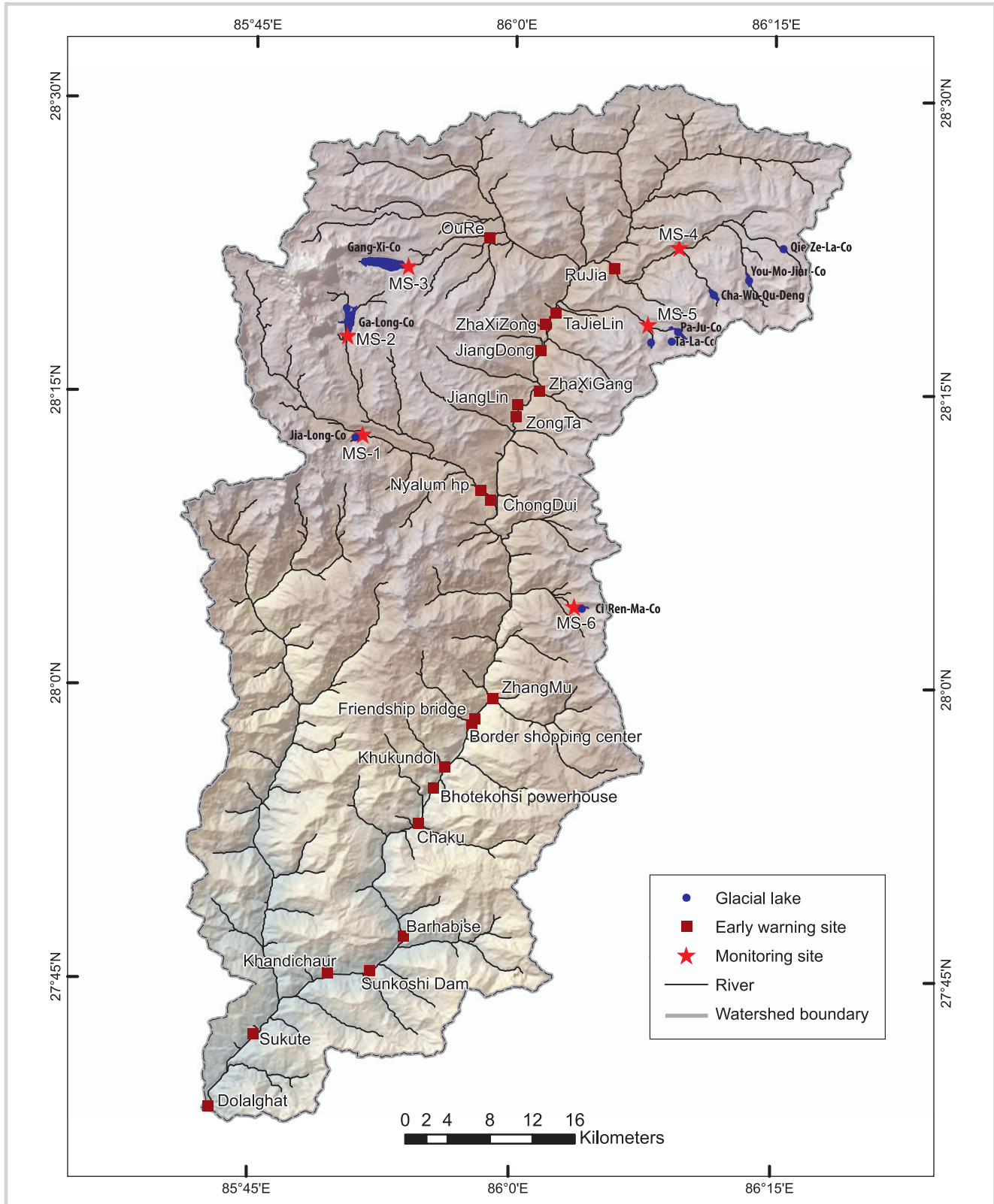
early-warning system in Nepal does not provide sufficient lead time to manage the risk.

Conclusion

The Poiqu/Bhote Koshi/Sun Koshi is a transboundary river and prone to GLOFs. Glacial lakes have been expanding as a result of glacier recession. This study identified 10 critical lakes in the watershed with a potential for a GLOF outburst based on the characteristics of the lake, glacier, dam, and surroundings. An empirical equation derived using data from the HKH region appeared to improve the estimation of lake volume from lake area but needs to be checked and modified using more field data. The range of possible peak discharges estimated using published empirical equations was very large. The maximum peak discharge estimated using empirical equations for Ci-Ren-Ma-Co (Zhangzambu) was within the estimates for peak discharge for the 1981 GLOF based on field measurement of channel geometry and water level, but for Ga-Long-Co lake the estimates were far higher than the modeled discharge. Further studies are needed to improve

estimates of peak discharge and understand the contribution of sediment in modeling GLOF. The level of GLOF risk in terms of potential economic loss is likely to increase in the watershed, as the volume of international trade is increasing and new hydropower projects are planned and under construction.

GLOF risk reduction strategies should focus on (1) limiting the exposure of life, property, and infrastructure in flood-prone areas by formulating and implementing land use guidelines and building codes and standards; (2) improving livelihood and service facilities in communities that are more vulnerable to flood risk; (3) improving awareness and skills among people with less adaptive capacity; and (4) establishing monitoring and early-warning systems. The most important early-warning need is for more lead time for those downstream to respond to a GLOF event. This requires monitoring as far upstream as possible, real-time transmission of information from monitoring sites, and rapid forwarding to warning systems—all of which will require strong bilateral cooperation. Mechanisms are also needed for sharing information on GLOFs between countries and at the local and regional levels.

DISCLAIMER

The views and interpretations in this publication are those of the authors and are not necessarily attributable to their organizations. They do not imply the expression of any opinion concerning the legal status of any country, territory, city, or area of authority; the delimitation of frontiers or boundaries; or the endorsement of any product.

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Supplemental material

Table S1 Area of glacial lakes and estimated volume of water used to derive equation 3.

Table S2 Glacial lake inventory. Glacial lake inventory. (During verification, some of the lake polygons were deleted because they were too small; the total number of lakes selected for the study amounts to 74.)

All found at DOI: httpx://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00009.S1 (116 KB PDF).