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Though glacial lake outburst floods have become an urgent issue on the Tibetan Plateau, no standardized methods have been proposed so far to identify and prioritize potentially dangerous glacial lakes (PDGLs). Here, we developed a first-order approach to identify PDGLs in the Boshula Mountain Range, southeastern Tibetan Plateau. Five variables—mother glacier area, distance between lake and glacier terminus, slope between lake and glacier, mean slope of moraine dam, and mother glacier snout steepness—were selected to identify PDGLs on the basis of four criteria we suggested. A fuzzy consistent matrix method was then applied to determine the weight of variables, and characteristic statistical values were used as thresholds to classify each variable. Out of 78 moraine-dammed lakes studied, we identified 8 glacial lakes as potentially very highly dangerous. We also validated our approach with 6 drained glacial lakes inside and outside our study area. Successfully identifying them as potentially very highly and/or highly dangerous lakes demonstrates the validity of the method.

Keywords: *Potentially dangerous glacial lakes; glacial lake outburst floods (GLOFs); moraine-dammed lake; southeastern Tibetan Plateau; China.*

Introduction

There are many glacial lakes on the Tibetan Plateau, and some of them have drained suddenly in recent years, producing glacial lake outburst floods (GLOFs) (Xu 1988; Ding and Liu 1992; Chen et al 1999). Such floods mainly occurred in the drainage basins of the Brahmaputra, Pumqu, and Poiqu rivers in south and southeast Tibet (Cheng et al 2008), where Tibetans live and where the climate is significantly influenced by the Asian summer monsoon. It is thus important to evaluate the potential risk of GLOFs in this region.

Several researchers have already developed approaches to assess glacial lake hazards worldwide, including remote sensing (Huggel et al 2002; Kääb et al 2005; Allen et al 2008; Fujita et al 2008), geographic information systems (GIS) (Huggel et al 2003, 2004b), and/or statistical (McKillop and Clague 2007b) and empirical (Huggel et al 2004a; McKillop and Clague 2007a) methods. Among these methods, remote sensing is regarded as the best way to extensively investigate glacial lakes and the impact of GLOFs in inaccessible glacier mountainous areas (Bolch et al 2008). Note that although these remote sensing-based methods are usually developed to evaluate glacial lakes in particular regions of concern (eg Huggel et al 2002, 2003 in the Swiss Alps; McKillop and Clague 2007a, 2007b in British Columbia; and Hegglin and Huggel 2008 in the Cordillera Blanca), their applicability to other mountainous regions, such as the southeastern Tibetan Plateau, warrants further study. In addition, some data of high quality in the aforementioned studies are not available or are difficult to acquire for the Tibetan Plateau area because of various factors. Using limited available data to assess the hazards of expanding glacial lakes in Tibet is therefore a challenge.

Here, we used readily available remotely sensed data—topographic maps; digital elevation models (DEMs); and Landsat, ALOS (Advanced Land Observing Satellite) AVNIR-2 (Advanced Visible and Near Infrared Radiometer type 2) imageries (Table 1)—to qualitatively evaluate the status of 78 moraine-dammed lakes whose area is larger than 0.02 km^2 in the Boshula Mountain Range (Wang et al 2011; 96.25°–96.75°E, 29.5°–30°N), southeastern Tibetan Plateau (Figure 1). Our endeavor lies in developing a first-order method to detect

TABLE 1 Remote sensing data used in this study and the applications.

Source/sensor	Date	Resolution/scale	Application
Topographic maps	1970s	1:50,000	Supplementary data
Landsat TM	2005–9–8	30 m	Supplementary data
ALOS AVNIR-2	2009–10–14	10 m	Mother glacier area, distance between glacier terminus and nearest lakeshore measurement
DEM	1970s	1:50,000	ALOS AVNIR-2 orthorectification, slope between lake and glacier, moraine dam slope, and glacier snout steepness identification

potentially dangerous glacial lakes (PDGLs) in the study area with limited data.

Selecting variables to identify PDGLs

Though GLOFs have recently become one of the primary natural hazards on and around the Tibetan Plateau, no uniform criteria have been introduced to identify PDGLs. Previous studies have indicated that the possibility of a glacial lake outburst is a function of several variables (Chen et al 1999; Lü 1999; RGSL 2003; Bajracharya et al 2007; McKillop and Clague 2007b; Wang et al 2008). Based on previously drained glacial lakes on the Tibetan Plateau, Lü (1999) suggested 7 variables for predicting PDGLs in Tibet (Table 2). McKillop and Clague (2007b) listed 18 variables on the basis of previously published accounts of moraine dam failures all over the world (Table 3). However, some of those proposed variables can only be detected from high-resolution satellite images or through field observation. It seems to be impracticable for a regional glacial lake evaluation on the Tibetan Plateau because we cannot laboriously investigate each lake in the field, taking into consideration that the remoteness and harsh weather conditions may hamper our measurements on the ground.

We therefore propose 4 criteria to filter candidate variables to identify PDGLs in our study area. First, variables should be measured using readily available, remotely sensed data (eg topographic maps, medium resolution of Landsat, ALOS imageries, and DEMs). Therefore, variables such as lake water volume, width of the moraine dam crest (Lü 1999), glacier calving front width (Richardson and Reynolds 2000) and moraine height-to-width ratio (Clague and Evans 2000; Huggel et al 2002) were exempted from our consideration, as they can only be measured on high-resolution data or in the field. Second, only variables proposed according to characteristics of previously outburst lakes on the Tibetan Plateau were included. With this criterion, such variables as lake freeboard (Blown and Church 1985) and lake freeboard-to-moraine crest height ratio (Huggel et al 2004a) were abandoned because they were based on drained lakes in the Swiss Alps and British Columbia. Third, the data type of variables had to be continuous

rather than nominal, because the quantitative values were used to classify variables (Table 3, see also next section). Fourth, variables should act independently and should not be reproducible from each other. For example, only 2 variables of lake–glacier proximity, lake–glacier relief, and slope between lake and glacier snout can calculate the other one, which was thought to be redundant.

Five variables met the 4 criteria, including (1) mother glacier area, (2) distance between lake and glacier terminus, (3) slope between lake and glacier, (4) mean slope of moraine dam, and (5) mother glacier snout steepness. Among these, mother glacier area reflects the area of accumulation and glacier snout and suggests the magnitude of snow and ice avalanche if it happens. Distance and slope between lake and mother glacier help project the possibility of ice avalanche into the glacial lake. The mean slope of the moraine dam dictates the dam's stability, and the steepness of glacier snout reflects the potentiality that the glacier tongue might crack.

The 5 variables were easily obtained from available satellite images and DEM. Mother glacier area and the distance between mother glacier and lake can be measured using ALOS imagery. Slope between lake and glacier was calculated based on the height difference between glacier terminus and the nearest lakeshore as well as the distance between mother glacier and lake. For the case where the glacier terminus was directly connected with the lake, it was represented by mother glacier snout steepness. A 100-m buffer zone outward from the glacial lake was approximately defined as moraine dam because most dam breaches are within this range (Lü 1999), and the horizontally lower most 500 m of glacier, where ice avalanche most likely occurs (Alean 1985), was defined as glacier snout. The mean slope of moraine dam and glacier snout can be calculated automatically after defining the outline of moraine dam and glacier snout in the slope grid generated from DEM with a resolution of 25 m.

Determining the weights of variables

It is necessary to assign a weight to each variable because they have a different influence on the potential risk of a glacial lake outburst. We used a fuzzy consistent matrix

FIGURE 1 Glacial lakes and glaciers in the study area, the Boshula Mountain Range. Red square inside indicates the approximate location of the study area on the Tibetan Plateau.
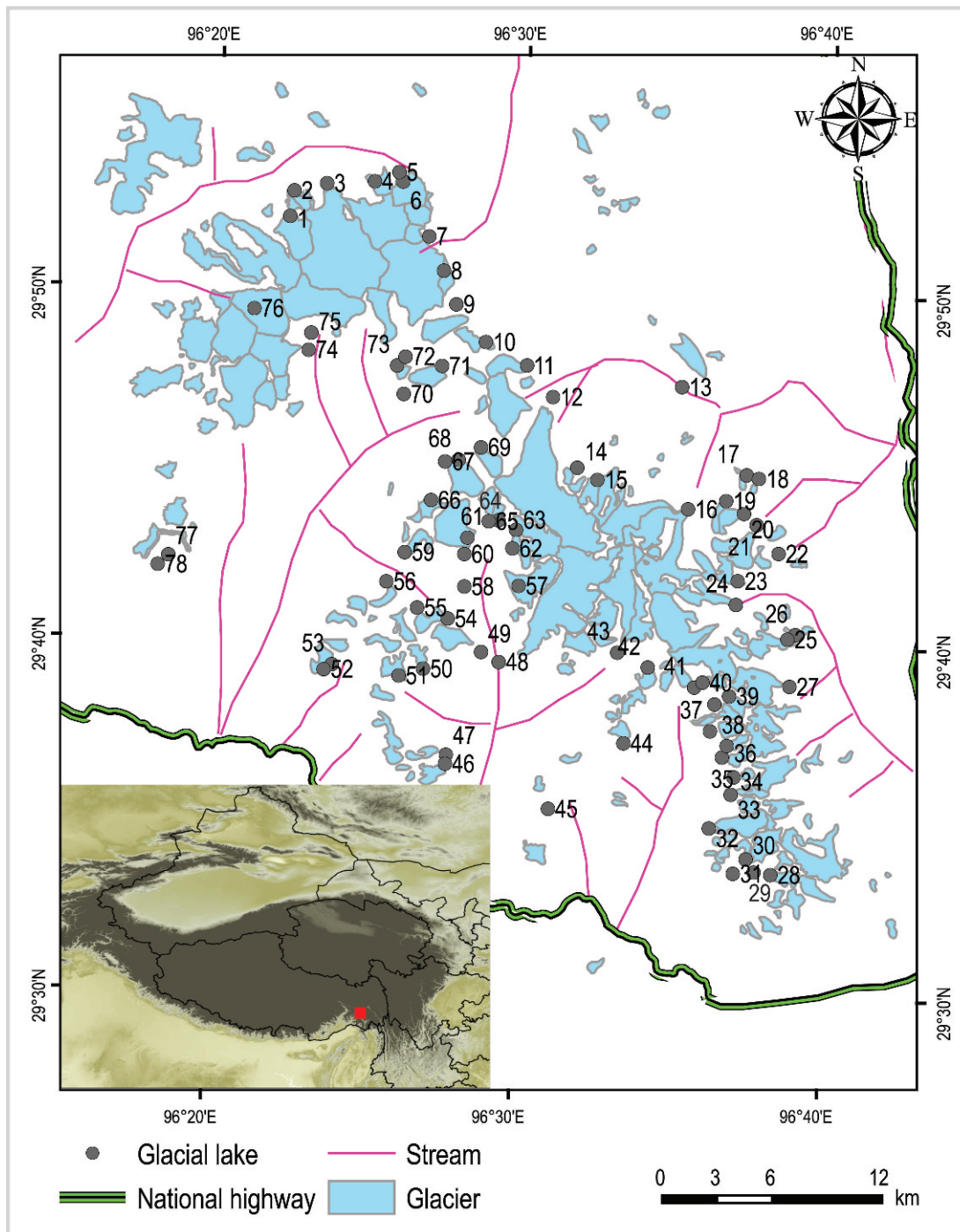
(FCM) method (Yao and Zhang 1997) to estimate the relative weights of each of the 5 variables. FCM, $(A_{ij})_{m*n}$, is a matrix of pairwise comparison of the importance of variables, where $0 \leq A_{ij} \leq 1$ and $A_{ij} + A_{ji} = 1$. A_{ij} is the membership of the importance of variable A_i with regard to A_j, so the larger A_{ij} is, the more important A_i is than A_j.

If $A_{ij} = 0.5$, variable A_i is as equally important as A_j (Huang et al 2005).

We constructed FCM (Table 4) based on outburst causes of historically drained glacial lakes in Tibet (Table 5) combined with empirical knowledge. Triggering mechanisms for GLOFs in Tibet can be overtopping

TABLE 2 Candidate predictor variables to identify PDGLs in Tibet suggested by Lü (1999), according to compiled information of previously outburst glacial lakes in Tibet.

Variables	Variation range of drained lakes	Value favorable for a lake to outburst
Watershed area (km^2)	2–30	>2
Slope of accumulation area of mother glacier (°)	7–12	>7
Slope of glacier tongue (°)	3–20	>8
Distance between glacier and lake (m)	8–500	<500
Lake water volume (10^8 m^3)	0.03–2.5	>0.01
Width of crest of moraine dam (m)	3–1,000	<60
Slope of downstream face of moraine dam (°)	25–33	>20

induced by ice avalanches slumping into the lake or piping due to thawing of buried dead ice beneath the moraine dam (Table 5). The former mechanism has dominated in the past. Therefore, distance and slope between lake and glacier as well as mother glacier snout steepness—which reflect the probability of ice avalanche—were thought to be more important than the other 2 variables. The weights of each of the 5 variables (w_{1-5}) were thus calculated, respectively, as 0.07, 0.27, 0.22, 0.195, and 0.245, using the following formula (Huang et al 2005):

$$w_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na} \sum_{k=1}^{n} A_{ik} \tag{1}$$

TABLE 3 Candidate predictor variables summarized by McKillop and Clague (2007b).

No.	Variable	Data type
1	Lake freeboard (m)	Continuous
2	Lake freeboard-to-moraine crest height ratio	Continuous
3	Lake area (km^2)	Continuous
4	Moraine height-to-width ratio	Continuous
5	Moraine distal flank steepness (°)	Continuous
6	Moraine vegetation coverage	Nominal
7	Ice-cored moraine	Nominal
8	Main rock type forming moraine	Nominal
9	Lake-glacier proximity (m)	Continuous
10	Lake-glacier relief (m)	Continuous
11	Slope between lake and glacier snout (°)	Continuous
12	Crevassed glacier snout	Nominal
13	Glacier calving front width (m)	Continuous
14	Glacier snout steepness (°)	Continuous
15	Snow avalanches enter lake	Nominal
16	Landslides enter lake	Nominal
17	Unstable lake upstream	Nominal
18	Watershed area (km^2)	Continuous

TABLE 4 Constructed FCM of 5 variables.

	A1[a]	A2[b]	A3[c]	A4[d]	A5[e]
A1	0.50	0.10	0.20	0.25	0.15
A2	0.90	0.50	0.60	0.65	0.55
A3	0.80	0.40	0.50	0.55	0.45
A4	0.75	0.35	0.45	0.50	0.40
A5	0.85	0.45	0.55	0.60	0.50

[a]Mother glacier area.
[b]Distance between lake and glacier terminus.
[c]Slope between lake and glacier.
[d]Mean slope of moraine dam.
[e]Mother glacier snout steepness.

TABLE 5 Documented glacial lake outbursts in Tibet and their causes.

Lake	Longitude	Latitude	Outburst date	Cause
Taraco	86°07′54″	28°17′ 29″	1935–08–28	Melt of dead ice
Qubixiama	85°02′24″	27°42′30″	1940–06–10	Ice avalanche
Sangwang	90°40′00″	28°24′54″	1954–07–16	Ice avalanche
Hailuogou	102°00′00″	29°32′00″	1955–07	Melt of dead ice?
			1966–07	Melt of dead ice?
			1976–08–30	Melt of dead ice?
Zhangzangbo	85°51′25″	28°10′38″	1964–07	Melt of dead ice?
			1981–07–11	Ice avalanche
Longda	85°00′25″	28°24′46″	1964–08–25	Ice avalanche
Gelhaipu	87°48′31″	27°57′50″	1964–09–21	Ice avalanche
Damenhai	93°09′15″	29°56′20″	1964–09–26	Ice avalanche
Ayaco	86°29′33″	28°20′49″	1965–08–15	Ice avalanche
			1969–08–17	Ice avalanche
			1970–08–18	Ice avalanche
Bugyai	94°48′36″	31°46′20″	1972–07–23	Ice avalanche
Zari[a]	90°48′30″	28°22′50″	1981–06–24	Ice avalanche
Zirema[a]	86°03′54″	28°04′36″	1981–07–11	Ice avalanche
Jinco[a]	87°38′29″	28°11′39″	1982–08–27	Ice avalanche
Guangxie[a]	94°30′00″	29°30′00″	1988–07–15	Melt of dead ice
Unknown 1[a]	96°33′25″	29°45′19″	1991–06–12	Figure 7 in Wang et al 2011
Unknown 2[a]	96°27′56″	29°45′12″	During 2005–2009	
Degapu			2002–09–18	Ice avalanche
Zhemaico			2009–07–03	Ice avalanche
Cilaco			2009–07–29	Ice avalanche

[a]Glacial lakes were used as a sample to validate the method of identifying PDGLs.

FIGURE 2 Mother glacier area (A), distance between lake and glacier terminus (B), slope between lake and glacier (C), mother glacier snout steepness (D), and mean slope of moraine dam (E) for the 78 moraine-dammed glacial lakes. Middle of the box is median and box width is defined by interquartile range (25th and 75th percentiles). Whiskers are 10th and 90th percentiles. Holly squares and stars are mean and min–max values.
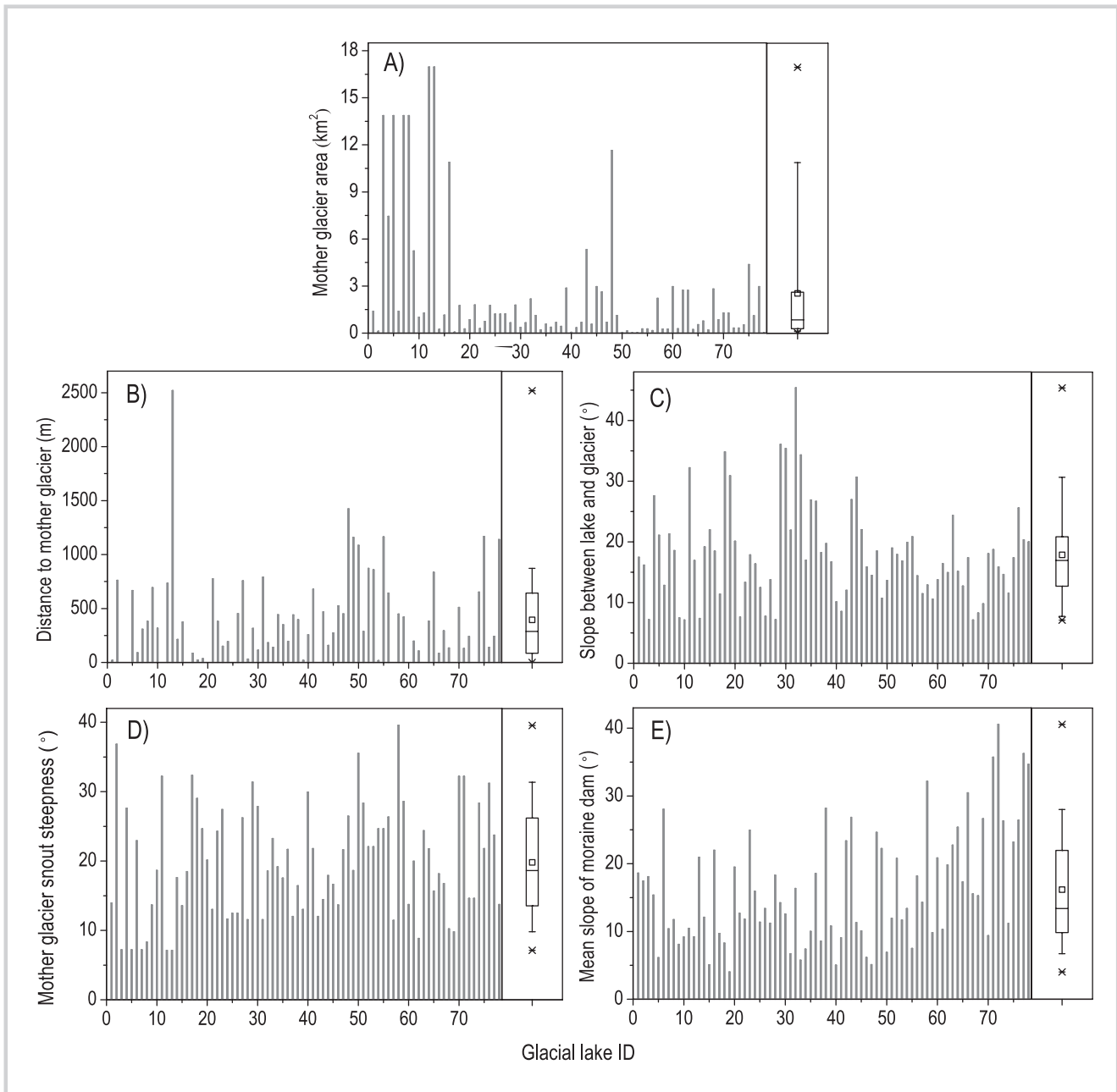
where

$$a = (n-1)/2 \qquad (2)$$

Classification of variables

Each glacial lake was labeled with a unique identity number from GL1 to GL78 (Figure 1). Figure 2 shows the values of 5 variables for all of the 78 moraine-dammed lakes in the study area. We then classified each variable into 4 intervals on the basis of the data's statistical distribution. The 25th percentile, median, and 75th percentile of each variable were used as cutoff values to equally screen the number of glacial lakes into each group, and then each group was assigned a danger value (V) from 0.25 to 1 (Table 6). Finally, the total value (P) of each glacial lake was calculated as:

$$P = \sum_{i=1}^{5} w_i \cdot V_i \qquad (3)$$

TABLE 6 Cutoff thresholds of each variable and the dangerous value for each interval.

| Interval	I	II	III	IV
Danger value (V)	0.25	0.5	0.75	1
Mother glacier area (km²)	<0.5	0.5–1	12.5	>2.5
Distance between lake and glacier terminus (m)	>600	300–600	80–300	<80
Slope between lake and glacier (°)	<12	12–17	17–21	>21
Mean slope of moraine dam (°)	<10	10–14	14–22	>22
Mother glacier snout steepness (°)	<14	1419	19–26	>26

where w_i is the weight of variable A_i and V_i is the danger value in Table 6. With the breaks in the cumulative curve and statistical characteristic values of P's distribution (Figure 3), we classified outburst potential for a glacial lakes as very high ($P > 0.8$), high ($P = 0.7–0.8$), medium ($P = 0.5–0.7$) and low ($P < 0.5$) to select approximately 10%, 15%, 50%, and 25% in each group. With these thresholds defined, we identified 8 glacial lakes as having a very high outburst potentiality. The details of these 8 glacial lakes are given in *Supplemental data*, Appendix S1 (http://dx.doi.org/10.1659/MRD-JOURNAL-D-10-00059.S1).

Validation of the method

To validate our method of identifying PDGLs, we applied the method to the drained glacial lakes inside and outside our study area. Only 2 glacial lakes in the study area had a

previous outburst, as revealed by satellite images (see Figure 7 in Wang et al 2011), so the sample may not be sufficient to validate the method. We therefore added another 4 drained glacial lakes along the Himalayan region to supplement our validation database (see also Table 5). We did not take all lakes listed in Table 5 in our validation database because no remotely sensed data were available to represent the status of these glacial lakes before outburst. We used topographic maps (1970s) and corresponding DEMs (constructed from topographic maps) to measure the 5 variables of these 6 drained glacial lakes to obtain the status of lakes before outburst (*Supplemental data*, Appendix S1; http://dx.doi.org/10.1659/MRD-JOURNAL-D-10-00059.S1). According to our methods, the 6 lakes are identified as having a very high and/or high risk of being PDGLs ($P > 0.7$), which is consistent with the fact that they drained in the past, and thus verifying the validity of our method to

FIGURE 3 The total value (P) for all 78 moraine-dammed lakes. The line is the cumulative curve of the distribution of P. Frame on the right: the box and whisker plot shows the statistical characteristic values. Symbols represent same meaning as in Figure 2. $P > 0.8$, $P = 0.7–0.8$, $P = 0.5–0.7$, and $P < 0.5$ were classified, respectively, as very high, high, medium, and low potentially dangerous lakes.
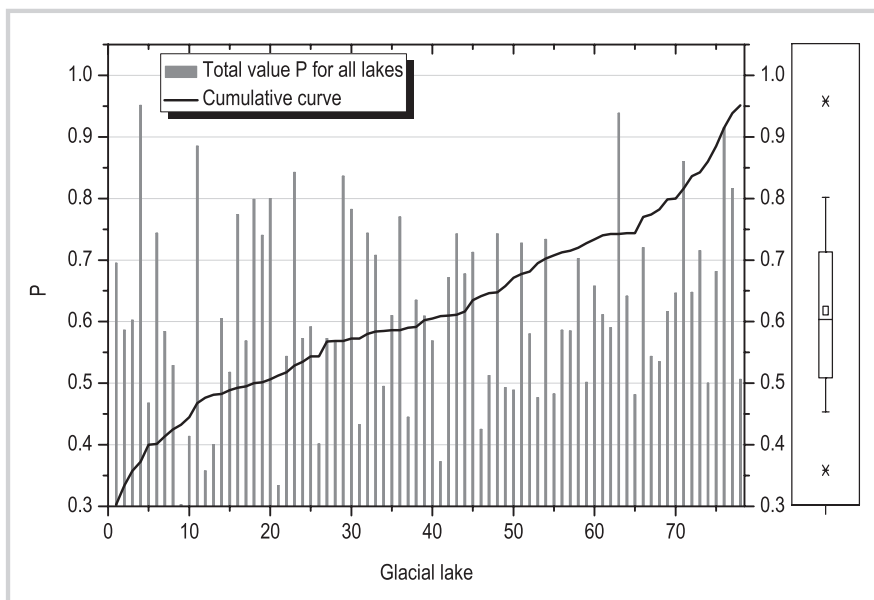
evaluate the potential outburst danger of glacial lakes in southeast Tibet.

Discussion and conclusion

We provided an easy way to qualitatively evaluate the degree of danger of glacial lakes using 5 suggested variables. Though it is certainly not possible to accurately predict when glacial lakes will outburst, our method can evaluate the status of glacial lakes in the study area and prioritize the potentially unstable glacial lakes for further assessment. Note, however, that some glacial lakes labeled as medium and low potentially dangerous lakes using our method ($P < 0.7$) may also produce catastrophic floods in the future, as other factors (eg extreme precipitation in the monsoon season, geotechnical characteristics of the moraine dam) can lead to the breach of these glacial lakes. Also, the evolution of glacial lakes is a dynamic process. With lake expansion and glacier melt, glacial lakes with a low hazard potentiality can evolve into potentially highly dangerous ones. However, the increasing frequency of GLOFs on the Tibetan Plateau (Richardson and Reynolds 2000) and limited manpower and resources in Tibet compel us to first resolve the problems posed by glacial lakes with a visibly high-hazard potential. Meanwhile, we need to intensify our monitoring of glacial lakes, to acquire the latest satellite imagery so as to identify new PDGLs as soon as possible.

We chose the 5 variables in our method based on 4 criteria. Among them, 2 of the variables (mother glacier area and glacier snout steepness) are related to the glacier, 2 (distance and slope between lake and glacier) to the lake–glacier relation, and 1 (mean slope of moraine dam) to the moraine dam. From historical documents on previously outburst glacial lakes, the dominant factor leading to GLOFs in Tibet has been overtopping induced by ice avalanche (Table 5). For this type of glacial lake, the 5 variables seem to be sufficient for evaluating their potentially dangerous status as the variables have already combined the status of the glacier and glacial lake, the instability of the moraine dam, and the triggering mechanism. However, for other causes of glacial lake outbursts—such as melt of dead ice and presence of ice core beneath the moraine dam—variables other than the 5 variables presented here may be more suitable to predict PDGLs. Therefore, applying the method to predict this type of glacial lake may not be as accurate as the former type. But considering the fact that more than three quarters of outburst glacial lakes in Tibet were caused by ice avalanches (Table 5, Wang et al 2009), by and large the 5 variables can represent the status of most PDGLs in Tibet.

We assigned a weight to each variable according to characteristics of historically drained glacial lakes combined with empirical knowledge. The applied FCM method can convert the qualitative description into quantitative numbers when conducting pairwise

comparison of variables. We ranked the variables in order of importance: distance from lake to glacier, mother glacier snout steepness, slope between lake and glacier, mean slope of moraine dam, and mother glacier area. Close study of most of the potentially very highly dangerous glacial lakes in the southeast Tibet (*Supplemental data*, Appendix S1; http://dx.doi.org/10.1659/MRD-JOURNAL-D-10-00059.S1) showed that the terminus of the mother glacier with a precipitous glacial tongue is very close or directly connected to the moraine-dammed glacial lake. In addition, we also divided each variable into 4 groups with critical values (ie 25th percentile, median, and 75th percentile) to make sure that each interval had the same number of glacial lakes. This is also applicable in the Himalayas where an inventory of glaciers and glacial lakes was available (ICIMOD 2005). With the attribute database of glaciers and glacial lakes in the Himalayas and ASTER Global Digital Elevation Model, we reclassified the 5 variables on the basis of numerical distribution characteristics (ie 25th percentile, median, and 75th percentile) and reanalyzed the PDGLs in Nepal and Bhutan identified by the International Centre for Integrated Mountain Development (ICIMOD). Of 44 analyzed PDGLs, 32 were labeled as potentially very highly and/or highly dangerous. Discrepancies may be caused by the different criteria defined in identifying PDGLs as ICIMOD gave greater importance to glacial lake area, whereas our method did not take this variable into consideration at all.

Our method is simple and the variables described in our method can be easily obtained from medium-resolution remotely sensed data and DEM. This is especially suitable in Tibet, where high-resolution satellite images and DEMs are sometimes not available or are available only at a high cost. Previous comprehensive methods of assessing GLOF hazards provided by Huggel et al (2002, 2004a) and McKillop and Clague (2007a, 2007b) were mainly based on outburst floods in the Swiss Alps or British Columbia, and they also relied on high resolution of remote sensing data (eg IKONOS satellite image or aerial photograph) or field observation. However, the data applied in this study are relatively easy to access, so the applicability of our method to other regions of the Tibetan Plateau may be promising.

Supplemental data

APPENDIX S1 Potentially very highly dangerous glacial lakes ($P > 0.8$) identified in our study area and their corresponding parameters (8 glacial lakes). Lake area uncertainties are obtained with a shoreline length multiplied by half a cell resolution of the ALOS image. Also shown are the characteristics of 6 drained glacial lakes obtained from topographic maps and corresponding DEMs.

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REFERENCES

Alean J. 1985. Ice avalanches: Some empirical information about their formation and reach. *Journal of Glaciology* 31:324–333.

Allen S, Owens I, Sirguey P. 2008. Satellite remote sensing procedures for glacial terrain analyses and hazard assessment in the Aoraki Mount Cook region, New Zealand. *New Zealand Journal of Geology and Geophysics* 51:73–87.

Bajracharya B, Shrestha AB, Rajbhandari L. 2007. Glacial lake outburst floods in the Sagarmatha region: Hazard assessment using GIS and hydrodynamic modeling. *Mountain Research and Development* 27:336–344.

Blown I, Church M. 1985. Catastrophic lake drainage within the Homathko River basin, British Columbia. *Canadian Geotechnical Journal* 22:551–563.

Bolch T, Buchroithner MF, Peters J, Baessler M, Bajracharya S. 2008. Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Natural Hazards and Earth System Sciences* 8:1329–1340.

Chen C, Wang T, Zhang Z, Liu Z. 1999. Glacial lake outburst floods in upper Nainchu River basin, Tibet. *Journal of Cold Regions Engineering* 13:199–212.

Cheng Z, Zhu P, Dang C, Liu J. 2008. Hazards of debris flow due to glacier lake outburst in southeastern Tibet [in Chinese with English abstract]. *Journal of Glaciology and Geocryology* 30:954–959.

Clague JJ, Evans SG. 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews* 19:1763–1783.

Ding Y, Liu J. 1992. Glacier lake outburst flood disasters in China. *Annals of Glaciology* 16:189–184.

Fujita K, Suzuki R, Nuimura T, Sakai A. 2008. Performance of ASTER and SRTM DEMs, and their potential for assessing glacier lakes in the Lunana region, Bhutan Himalayas. *Journal of Glaciology* 54(185):220–228.

Hegglin E, Huggel C. 2008. An integrated assessment of vulnerability to glacial hazards: A case study in the Cordillera Blanca, Peru. *Mountain Research and Development* 28:299–309.

Huang J, Wang C, Wang G, Zhang C. 2005. Application of fuzzy comprehensive evaluation method in risk degree determination for ice-lake outburst: An example of LUOZHA county in Tibet [in Chinese with English abstract]. *Earth and Environment* 33:109–114.

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

Huggel C, Kääb A, Haeberli W, Krummenacher B. 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: Evaluation and application in the Swiss Alps. *Natural Hazards and Earth System Sciences* 3: 647–662.

Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F. 2002. Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps. *Canadian Geotechnical Journal* 39:316–330.

Huggel C, Kääb A, Salzmann N. 2004b. GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. *Norwegian Journal of Geography* 58:61–73.

ICIMOD [International Centre for Integrated Mountain Development]. 2005. Inventory of glaciers, glacial lakes and identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region. www.rrcap.unep.org/issues/glof/glof/index.htm; accessed on 15 January 2011.

Kääb A, Huggel C, Fischer L, Guex S, Paul F, Roer I, Salzmann N, Schlaefli S, Schmutz K, Schneider D, Strozzi T, Weidmann Y. 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences* 5:527–554.

Lü R. 1999. *Debris Flow and Environment in Tibet* [in Chinese]. Chengdu, China: Chengdu Science and Technology University Press.

McKillop RJ, Clague JJ. 2007a. A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. *Natural Hazards* 41:131–157.

McKillop RJ, Clague JJ. 2007b. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in Southwestern British Columbia. *Global and Planetary Change* 56:153–171.

RGSL [Reynolds Geo-Sciences Ltd]. 2003. Development of glacial hazard and risk minimisation protocols in rural environments: methods of glacier and lake inventory compilation with specific reference to hazard assessment. www.bgs.ac.uk/research/international/reportSearch.cfm; accessed on 15 January 2011.

Richardson SD, Reynolds JM. 2000. An overview of glacial hazards in the Himalayas. *Quaternary International* 65/66:31–47.

Wang W, Yao T, Yang X. 2011. Variations of glacial lakes and glaciers in the Boshula mountain range, southeast Tibet, from the 1970s to 2009. *Annals of Glaciology* 52(58):9–17.

Wang X, Liu S, Guo W, Xu J. 2008. Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida Lakes, China. *Mountain Research and Development* 28:310–317.

Wang X, Liu S, Guo W, Yu F, Xu J. 2009. Hazard assessment of moraine-dammed lake outburst floods in the Himalayas, China [in Chinese with English abstract]. *Acta Geographica Sinica* 64:782–790.

Xu D. 1988. Characteristics of debris flow caused by outburst of glacial lake in Boqu River, Xizang, China. 1981. *GeoJournal* 17:569–580.

Yao M, Zhang S. 1997. Fuzzy consistent matrix and its applications in soft science [in Chinese with English abstract]. *Systems Engineering* 15:54–57.