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Abstract: A glacial lake outburst flood (GLOF) is a typical glacier-related hazard in high mountain regions. In recent decades, glacial lakes in the Himalayas have expanded rapidly due to climate warming and glacial retreat. Some of these lakes are unstable, and may suddenly burst under different triggering factors, thus draining large amounts of water and impacting downstream social and economic development. Glacial lakes in the Poiqu River basin, Central Himalayas, have attracted great attention since GLOFs originating there could have a transboundary impact on both China and Nepal, as occurred during the Cirenmaco GLOF in 1981 and the Gongbatongshaco GLOF in 2016. Based on previous studies of this basin, we selected seven very high-risk moraine-dammed lakes (Gangxico, Galongco, Jialongco, Cirenmaco, Taraco, Beihu, and Cawuqudenco) to simulate GLOF propagation at different drainage percentage scenarios (i.e., 25%, 50%, 75%, and 100%), and to conduct hazard assessment. The results show that, when any glacial lake is drained completely or partly, most of the floods will enter Nepal after raging in China, and will continue to cause damage. In summary, 57.5 km of roads, 754 buildings, 3.3 km² of farmland, and 25 bridges are at risk of damage due to GLOFs. The potentially inundated area within the Chinese part of the Poiqu River basin exceeds 45 km². Due to the destructive impacts of GLOFs on downstream areas, appropriate and effective measures should be implemented to adapt to GLOF risk. We finally present a paradigm for conducting hazard assessment and risk management. It uses only freely available data and thus is easy to apply.

Keywords: GLOF; glacial lake; hazard assessment; Himalayas

1. Introduction

Increasing snow and ice meltwater is being detected in many glacierized areas due to climate warming and glacial retreat [1–6]. This situation greatly favors the formation and expansion of glacial lakes [7–9]. During the period of 1990 to 2015, the Himalayan glacial lakes increased 8% in number, from 4549 to 4950, and 14% in area, from 398 km² to 455 km² [10], thus increasing the potential risk of glacial lake outburst floods (GLOFs). A GLOF is a typical glacier-related hazard. It is defined as a large amount of water that suddenly flows out of a lake dammed by moraine, landslide, bedrock, or glacier-ice, and is characterized by high peak discharge and short duration [11]. Triggers for GLOF events are variable. When the area near a glacial lake is unstable and likely to generate snow/ice avalanches, landslides, and rockfalls, such lakes may be more susceptible to an outburst. When a heavy precipitation event triggers GLOF, the mixed flooding will cause a longer affected distance and larger inundated area [12,13].



Citation: Zhang, T.; Wang, W.; Gao, T.; An, B. Simulation and Assessment of Future Glacial Lake Outburst Floods in the Poiqu River Basin, Central Himalayas. *Water* **2021**, *13*, 1376. https://doi.org/10.3390/ w13101376

Academic Editor: Juan Antonio Ballesteros Canovas

Received: 17 April 2021 Accepted: 13 May 2021 Published: 15 May 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Among the different types of GLOFs, floods originating from moraine-dammed lakes have been extensively studied by scholars due to their uniform spatial distribution, obvious breach, and easy identification by remote sensing images. Since 1900, more than 150 such GLOF events have been identified in the Himalayas [14–16], and more than half were caused by snow/ice avalanches [17]. Unfortunately, several catastrophic GLOFs have caused thousands of deaths in the Himalayas [18]. The most devastating GLOF event occurred on 16 June 2013, killing more than 6000 people in India [19,20].

Previous studies largely focused on the distribution of and changes to glacial lakes [7–10,21], the identification of potentially dangerous glacial lakes [22–29], and the reconstruction of GLOF processes [30–35]. However, only sporadic research has been conducted involving future GLOF simulation and detailed downstream hazard/risk assessment in specific regions of the Himalayas [26,36–38]. Therefore, there is an urgent need to predict the impact of future GLOFs on downstream areas, estimate the flood path, depth, and velocity, and prepare hazard maps for scientific and policymaking usage.

In this study, we selected a glacierized catchment, the Poiqu River basin of the Central Himalayas, as an experimental site for conducting GLOF simulation. We also present an easily applied paradigm for assessing GLOF hazard. Our specific goals were to: (i) model GLOFs from different high-risk moraine-dammed lakes, (ii) evaluate GLOF impacts under different lake drainage percentage scenarios (25%, 50%, 75%, and 100%), and (iii) draw hazard maps to provide reference for future prevention and mitigation measures. Based on previous glacial lake risk assessment results [26], we selected seven very high-risk moraine-dammed lakes—namely Gangxico, Galongco, Jialongco, Cirenmaco, Taraco, Beihu, and Cawuqudenco—in the Poiqu River basin to simulate outburst floods. We used HEC-RAS (Hydrologic Engineering Center River Analysis System) version 5.0.7 software to simulate the extent, velocity, and depth of GLOF inundation. We also collected information on infrastructure and farmland by digitizing high-resolution satellite images.

2. Study Area

2.1. Geographical and Climatic Setting

The Poiqu River basin is located on the southern slope of the Central Himalayas. This river is one of the main tributaries of the Ganges (Figure 1). Its watershed area is 2072 km². Due to the basin's large altitude differences, its climate includes the subtropical zone, warm temperate zone, cold temperate zone, and alpine tundra zone. Many studies have been conducted on temporal and spatial glacial lake changes, as well as hazard/risk assessment in the basin [26,36,39–41]. The latest results reveal that glacial lakes in the basin expanded by approximately 110% between 1964 and 2017, and the average retreat rate of glaciers was 1.4 km²·a⁻¹ between 1975 and 2015 [21]. The area had 59 glacial lakes with mother glaciers in 2018. Galongco is the largest glacial lake in the basin and has experienced steady growth for more than 40 years, expanding from 1.23 km² to 5.38 km² during the period 1976–2018.

According to observations from the Nyalam station (3810 m a.s.l.) of the China Meteorological Data Network (1967–2012), the basin's mean annual temperature was 3.7 °C, and mean annual precipitation was 650.7 mm. The six-year (2006–2011) average temperature at Zhangmu station (2480 m a.s.l.), south of Nyalam station, was 12.8 °C and the average precipitation was 2820 mm [31].



Figure 1. Study area. (**a**) Location of Poiqu River basin on regional map; (**b**) Poiqu River basin; (**c**–**e**) photos taken from a field investigation in October 2020, including (**c**) Cirenmaco, (**d**) Jialongco, and (**e**) Galongco.

2.2. Historical GLOFs

Twelve GLOFs occurred in the basin in the past 100 years. For example, the Taraco GLOF occurred on 28 August 1935. The resulting flood destroyed hundreds of acres of farmland and caused damage along 30 km of river channel [42]. Cirenmaco GLOFs occurred repeatedly in 1964, 1981, and 1983 (Figure 1c). The most severe event was the 1981 flood, which was marked by a peak discharge exceeding 16,000 m³·s⁻¹ and killed approximately 100 people downstream [40,42,43]. Other examples are the Jialongco GLOFs of 23 May and 29 June 2002 (Figures 1d and 2a). Enhanced glacier meltwater and precipitation presumably triggered the outburst, destroying the Nyalam Hydropower Station and approximately 27 km of road downstream, thus resulting in an economic loss of approximately USD 1.5 million [44]. A recent GLOF occurred on 5 July 2016 at Gongbatongshaco (Figure 2b). The flood destroyed a hydropower station in Nepal, causing an economic loss of approximately USD 70 million [15,45]. In addition, another five GLOFs which might have occurred before the 1980s were detected [41,46] (Figure 2c,d).



Figure 2. These photos demonstrate a distinct relationship between the shape of the breach and the eroded riverbed of GLOFs. A field investigation allowed us to observe flood traces at (**a**) Jialongco, (**b**) Gongbatongshaco, and (**c**,**d**) an unnamed lake reported by Veh et al. [46].

3. Data and Methods

3.1. Remote Sensing Data

As the first new satellite of the GaoFen (GF) series, GF1 produces multispectral remote sensing images with high spatial resolution and wide field of view (WFV). A total of three GF1 images—acquired on 12 December 2017, 28 December 2017, and 7 October 2018—were used to map buildings, roads, bridges, and certain other objects through manual identification. The High Mountain Asia (HMA) 8-meter digital elevation model (DEM), provided by the NASA Earth data (https://search.earthdata.nasa.gov/search, accessed on 20 December 2019) in 2017, was selected to provide input data for flood modeling. It is a digital elevation model of Asian high mountain glaciers and snowfall regions generated by high-resolution along-track and cross-track stereoscopic images from DigitalGlobe satellites [47]. In addition, several Landsat-5 TM and Sentinel-2A images were used to demonstrate lake evolution and outburst floods.

3.2. Potentially Dangerous Glacial Lakes

Following the 2019 study by Allen et al. [26], 10 very high-risk glacial lakes were highlighted on the Tibetan Plateau, of which seven are situated in the Poiqu River basin, namely Gangxico, Galongco, Jialongco, Cirenmaco, Taraco, Beihu, and Cawuqudenco (Table 1). These lakes were selected based on outburst susceptibility (hazard) and the exposure of downstream communities, and are better representatives (total 1291 glacial lakes, >0.1 km²) than other assessment results [36,40,41]. Of these seven potentially dangerous glacial lakes, Jialongco and Galongco are located upstream of Nyalam, threatening the safety of the urban area, and the remaining lakes generally threaten some villages, such as Ere, Rujie, and Jianggang (see Figure 1b for exact locations).

Lake	Long $^{\circ}$	Lat $^{\circ}$	Area (km²)	Elevation (m)	Lake Area Change (km ² /10a)	Risk Index [26]
Gangxico	85.87	28.36	4.57	5212	0.73	0.8
Galongco	85.31	28.84	5.38	5067	1.08	0.94
Jialongco	85.21	28.84	0.60	4360	0.12	0.87
Cirenmaco	86.06	28.06	0.29	4627	0.08	0.95
Taraco	86.13	28.29	0.23	5244	0.01	0.72
Beihu	86.15	28.30	0.56	5307	0.04	0.79
Cawuqudenco	86.19	28.33	0.53	5422	0.02	0.73

Table 1. Summary of potentially dangerous glacial lakes.

3.3. HEC-RAS Model and Parameters

HEC-RAS is a two-dimensional hydraulic model and has a wide range of applications in flood prediction and reconstruction [34,48–53]. Parameters such as lake volume, peak discharge, and outburst duration in flood modeling were obtained either by field investigation or by empirical estimation. They would be used to estimate the dam-breach hydrograph, which is significant to the precision of the model output. Additionally, a high-resolution DEM and a suitable land surface roughness value can also enhance the model output.

3.3.1. Estimating Lake Volume, Peak Discharge, and Breaching Time

Lake volume is the maximum amount of water that can be involved in a GLOF. The volume–area relationship for moraine-dammed lakes (with an R² value of 0.94, Equation (1)) proposed by Cook and Quincey (2015) [54] was used in this study. For Cirenmaco, we used a lake volume of 18×10^6 m³ based on an in-situ bathymetric survey to drive the model [31].

$$V = 60A - 6.2817 \times 10^6 \tag{1}$$

The peak discharge (Q_p) and the breaching time (T_p) were estimated using empirical equations [55,56]. Most of the equations predicting peak discharge tend to overestimate, and those predicting breaching time tend to underestimate. However, the Froehlich equations both have the lowest error compared with measured data after verification [57].

$$Q_{\rm p} = 0.607 V^{0.295} h_{\rm w}^{1.24}$$
⁽²⁾

$$T_{\rm p} = 0.00254 {\rm V}^{0.53} {\rm h_b}^{-0.9}$$
(3)

Here, V is the outburst volume, h_w is the depth of water above the breach invert at the time of failure (m), and h_b is the breach height (m). These three parameters are replaced by glacial lake volume, height difference between lake water surface elevation and moraine ridge bottom elevation, and height difference between moraine dam crest elevation and moraine ridge bottom elevation, respectively (Table 2). The elevation values are extracted from DEM.

Tabl	le 2.	GLOF	parameters	from a	comp	lete c	lrainage.
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Glacial Lake	V(10 ⁶ m ³)	h _b (m)	h _w (m)	T _p (min)	$Q_p (10^4 m^3/s)$
Gangxico	267.97	89	67	79	3.42
Galongco	316.52	95	80	81	4.47
Jialongco	29.72	74	62	29	1.62
Cirenmaco	18	72	63	23	1.43
Taraco	7.23	83	77	12	1.40
Beihu	27.04	87	76	24	2.03
Cawuqudenco	25.58	80	63	25	1.58

Furthermore, according to a model roughness sensitivity test and suggestions [31], 0.15 was selected as the roughness value for the channel and floodplain regions.

3.3.2. Dam-Breach Hydrograph

In the absence of measured or simulated data, the GLOF process line can be inferred indirectly [58,59]. We assume that the flood discharge will increase/decrease linearly. The outburst volume is then used as a control to draw the GLOF process line (Figure 3). This hypothetical method has been applied in many GLOF studies, and the results are in line with the actual situation [31,52,53].



Figure 3. Breach hydrograph used as input to simulate the outburst flood at different drainage percentages. The example of Cirenmaco is presented in this figure.

3.4. Hazard Index

Complete drainage in large or medium-sized lakes has been infrequent in previous GLOFs. Therefore, we divided the lake drainage percentage into four levels: 25%, 50%, 75%, and 100%. According to an inventory of GLOF events from nine moraine-dammed lakes in the Himalayas [46], we calculated the frequency of different lake drainage scenarios (Table 3). The results indicate that among these nine outburst lakes, only one glacial lake drained more than 75% of its water volume, four lakes drained 50–75%, two lakes drained 25–50%, and two lakes drained less than 25%. Corresponding to the percentage of lake drainage, we assumed that the probability is 0.11, 0.45, 0.22, and 0.22, respectively, for the four different scenarios. Finally, we proposed an index to assess the susceptibility and extent of damage from the GLOFs, and to classify the hazard levels of the Chinese part of the Poiqu River basin. This hazard index was calculated in a spatially distributed manner.

$$\mathbf{H} = \sum_{i=1}^{n} \max \left| \bigcup_{j=1}^{m} \left(R_i \times P_{ij} \times D_{ij} \times V_{ij} \right) \right|$$
(4)

Here, U is a union, R corresponds to the GLOF risk (Table 1), P is the likely GLOF volume from the same glacial lake in different scenarios, and D and V are the results of model running, representing the mean depth and velocity, respectively. *i* represents the seven very high-risk glacial lakes, with values ranging from 1 to 7, and *j* represents the four grades of breach water volume, with values ranging from 1 to 4. *m* corresponds to the four different drainage percentages and *n* corresponds to the seven very high-risk moraine-dammed lakes.

Additionally, the exposure of communities were estimated by summing the submerged buildings, farmland, roads, and bridges. Subsequently, the value was normalized into a range of 0–1. A value of 0 means that it would not be affected at all, and 1 means that it would be most affected.

ID	Lake	Outburst Date	Country	Long $^\circ$	Lat $^{\circ}$	Date of Last Clear Image before GLOF	Date of Last Clear Image after GLOF	Area before (10 ⁶ m ²)	Volume before (10 ⁶ m ³)	Volume after (10 ⁶ m ³)	Volume Change (%)
1	Tam Pokhari	3 September 1998	Nepal	86.84	27.74	1998-02-19	1998-10-17	0.58	10.03	4.59	54%
2	Chongbaxiaco	6 Âugust 2000	China	89.74	28.21	2001-07-23	2003-11-18	0.77	18.23	9.49	48%
3	Zangla Tsho	1994	China	82.14	30.34	1994-07-30	1994-09-09	0.23	6.61	2.21	67%
4	Rejieco	1992	China	88.89	27.97	1992-04-16	1992-11-10	0.27	8.76	4.18	52%
5	Zanglaco East	2015-2016	China	82.20	30.31	2015-09-05	2016-05-16	0.30	4.98	2.79	44%
6	Sangwangco East	2007–2008	China	90.23	28.28	2007-07-08	2008-12-17	1.04	28.76	23.05	20%
7	Changri Tsho III	1998	Bhutan	90.81	27.90	1997-11-01	1998-09-10	0.49	0.64	0.11	83%
8	Kongyangmi La Tsho	1994–1996	India	88.78	27.90	1994-10-31	1996-05-13	0.50	11.16	2.86	74%
9	Luggye Tsho	7 October 1994	Bhutan	90.30	28.09	1994-09-22	1994-11-09	1.22	32.21	24.11	25%

4. Results

4.1. Impact of GLOFs

The GLOF simulation results show that if any of the seven very high-risk glacial lakes drained, it would cause serious socioeconomic impacts to downstream areas, even under the smallest drainage scenarios. After the GLOF has raged in China, it is generally projected to continue to cause damage in Nepal (Table 4). For example, a Galongco outburst at 75% volume could inundate a downstream area of up to 11.92 km², with an average inundation depth of 17.45 m and an average flow velocity of 6.04 m/s. In addition, 12.02 km of roads and 132 buildings could be at risk (Figure 4a). A Jialongco GLOF (75% drainage scenario) could inundate an area of up to 5.61 km², with an average inundation depth of 10.91 m and an average flow velocity of 4.41 m/s (Figure 4b). Under these 75% drainage scenarios, the upper district of Nyalam (a new area developed recently) could be threatened by floods, while the lower main district would be less threatened by flooding due to its higher location (Figure 5).

Table 4. Parameters of GLOFs originating in different glacial lakes and causing damage in the Chinese part of the Poiqu River basin.

Glacial Lake	Breach Water Volume (%)	Trans- Boundary Impact	Flooded Area (km ²)	Mean Depth (m)	Max Depth (m)	Mean Veloc- ity (m/s)	Max Velocity (m/s)	Farmland (km ²)	Roads (km)	Buildings	Bridges
Gangxico	25	Yes	14.77	7.78	44.70	3.28	22.09	1.72	25.96	284	17
U	50	Yes	18.71	10.90	52.62	4.05	26.39	2.41	34.58	440	18
	75	Yes	21.40	13.21	57.78	4.56	28.45	2.76	40.55	507	18
	100	Yes	23.32	15.06	63.93	4.93	29.93	3.00	44.66	539	18
Galongco	25	Yes	8.76	10.26	47.87	4.45	23.71	-	8.93	79	10
0	50	Yes	10.59	14.31	62.25	5.42	27.81	-	11.20	111	10
	75	Yes	11.92	17.48	70.64	6.04	30.11	-	12.02	132	10
	100	Yes	13.20	19.14	76.67	6.30	29.46	-	12.51	140	10
Jialongco	25	Yes	4.09	6.27	37.04	2.98	11.02	-	3.67	34	10
	50	Yes	5.03	9.05	44.57	3.87	14.73	-	7.53	67	10
	75	Yes	5.61	10.91	47.68	4.41	16.55	-	9.38	75	10
	100	Yes	6.36	13.33	58.92	5.05	19.18	-	10.99	104	10
Cirenmaco	25	Yes	1.79	5.96	42.26	3.70	12.63	-	0.03		2
	50	Yes	2.23	8.75	47.94	5.24	18.14	-	0.04		2
	75	Yes	2.48	10.84	52.46	6.08	19.61	-	0.06		2
	100	Yes	2.71	12.85	56.73	6.73	22.32	-	0.05		2
Taraco	25	No	3.64	2.85	11.68	2.29	8.93	0.27	1.57	3	7
	50	No	5.59	4.46	27.58	2.91	10.65	0.56	4.01	11	11
	75	No	7.02	5.82	47.01	3.33	11.77	0.83	5.89	37	12
	100	Yes	8.54	7.51	49.98	3.82	13.28	1.10	8.69	85	13
Beihu	25	No	6.33	5.13	42.21	2.87	12.26	0.73	5.26	22	12
	50	Yes	8.54	7.74	45.64	3.66	15.24	1.15	9.37	90	13
	75	Yes	10.04	9.55	49.63	4.18	17.31	1.51	12.56	195	13
	100	Yes	11.20	11.12	53.04	4.62	18.96	1.70	15.40	268	13
Cawuqudenco	25	No	8.24	4.40	49.26	2.46	9.20	0.81	8.25	45	17
	50	Yes	10.48	6.31	54.94	3.06	11.99	1.15	13.26	109	18
	75	Yes	12.04	7.75	57.21	3.51	13.68	1.47	18.16	175	18
	100	Yes	13.01	9.04	59.30	3.87	15.95	1.86	21.98	322	18



Figure 4. Inundation maps for GLOFs originating in (**a**) Galongco, (**b**) Jialongco, (**c**) Gangxico, (**d**) Cawuqudenco, (**e**) Beihu, (**f**) Taraco, and (**g**) Cirenmaco under a 75% drainage scenario.



Figure 5. Velocity of GLOFs originating from (a) Galongco and (b) Jialongco under a 75% drainage scenario.

Gangxico is the second largest glacial lake in the Poiqu River basin. Several villages are located downstream. In the case of 75% outburst volume, the inundated area could be as large as 21.4 km², with an average inundation depth and flood velocity of 13.21 m and 4.56 m/s, respectively. It is projected that 40.55 km of roads, 2.76 km² of farmland, 507 buildings, and 18 bridges could be at risk during a GLOF (Figure 4c).

Cawuqudenco, Beihu, and Taraco are situated in the northeast of the Poiqu River basin and more than 14 villages are located downstream. If Taraco released 75% of its volume, the GLOF's peak discharge could reach 10,494 m³/s and the inundated area could be 7.02 km², with an average inundation depth of 5.82 m and an average flood velocity of 3.33 m/s. In addition, 5.89 km of highways, 0.83 km² of farmland, 37 buildings, and 12 bridges could be at risk. The destructiveness of the Cawuqudenco and Beihu GLOFs are similar to the Taraco GLOF (Figure 4d–f). Cirenmaco is the most dangerous glacial lake in the Poiqu River basin. If it suddenly drained (under a 75% drainage scenario), the inundated area could be as large as 2.48 km², with an average depth of 10.84 m (Figure 4g).

Considering the damage caused by outburst floods, the area between Dajie village and the Zhangdong Bridge upstream of the Poiqu River would be most severely impacted (Table 5). Because the valley here is relatively flat, roads and buildings are built close to the river.

Figure 6 displays the estimated arrival time of peak discharge in the main villages and towns. The large amount of water, high peak discharge, and long duration of a Gangxico GLOF could cause the most severe damage to the Poiqu River basin. Except for villages like Ere that are very close to the glacial lake and would be quickly inundated, other settlements would have enough time to evacuate since the GLOF is projected to travel a long distance before it enters the main channel of the Poiqu River. Taraco, Beihu, and Cawuqudenco GLOFs might take more than 30 minutes to flow from tributaries to the main stream. In addition, GLOFs from Jialongco or Galongco might take at least 55 minutes to reach the upper district of Nyalam, even in the fastest moving scenario. Therefore, a GLOF early warning system at the glacial lake would be an important measure to reduce the loss of life and property.

Glacial Lake	Breach Water Volume (%)	Ere	Rujie	Dajie	Zhangdong Bridge	Jiangdong	Lamu	Zhaxigang	Jianggang	Та	Nyalam	Friendship Bridge
Gangxico	25	0.47	0.02	0.3	0.42	0.22	0.09	0.1	0.21	0.45	0	0.08
0	50	0.71	0.05	0.37	0.55	0.27	0.22	0.22	0.23	0.79	0	0.08
	75	0.83	0.07	0.4	0.56	0.28	0.24	0.32	0.23	0.96	0.01	0.08
	100	0.9	0.1	0.45	0.57	0.29	0.24	0.37	0.23	1	0.02	0.09
Galongco	25	0	0	0	0	0	0	0	0	0	0.38	0.08
Ū	50	0	0	0	0	0	0	0	0	0	0.53	0.1
	75	0	0	0	0	0	0	0	0	0	0.61	0.13
	100	0	0	0	0	0	0	0	0	0	0.63	0.14
Jialongco	25	0	0	0	0	0	0	0	0	0	0.18	0.05
-	50	0	0	0	0	0	0	0	0	0	0.34	0.06
	75	0	0	0	0	0	0	0	0	0	0.37	0.08
	100	0	0	0	0	0	0	0	0	0	0.51	0.09
Cirenmaco	25	0	0	0	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0	0	0	0.01
	75	0	0	0	0	0	0	0	0	0	0	0.01
	100	0	0	0	0	0	0	0	0	0	0	0.01
Taraco	25	0	0	0.1	0.04	0.02	0.01	0.01	0.01	0.01	0	0
	50	0	0	0.19	0.1	0.03	0.01	0.01	0.01	0.01	0	0.03
	75	0	0	0.25	0.21	0.09	0.02	0.03	0.01	0.01	0	0.04
	100	0	0	0.33	0.34	0.19	0.04	0.06	0.03	0.01	0	0.05
Beihu	25	0	0	0.21	0.15	0.08	0.02	0.02	0.01	0.01	0	0.04
	50	0	0	0.25	0.18	0.12	0.06	0.07	0.03	0.01	0	0.05
	75	0	0	0.34	0.48	0.25	0.15	0.12	0.23	0.14	0	0.07
	100	0	0	0.39	0.54	0.26	0.18	0.17	0.23	0.38	0	0.08
Cawuqudenco	25	0	0.28	0.2	0.1	0.04	0.01	0.02	0.01	0.01	0	0.03
	50	0	0.46	0.26	0.24	0.11	0.02	0.05	0.01	0.01	0	0.05
	75	0	0.6	0.29	0.36	0.19	0.05	0.07	0.04	0.01	0	0.06
	100	0	0.69	0.33	0.46	0.24	0.11	0.11	0.2	0.39	0	0.07

Table 5. Potential impact of GLOFs from different glacial lakes on downstream villages and towns. The values are in the range of 0–1, which is calculated from the number of submerged buildings, farmland, roads, and bridges between the sections of the villages. It represents the exposure of communities and infrastructure to the risk of GLOFs.

1

0

Ó

20

40

60



Distance from breach(km) Distance from breach(km) Map view of region Figure 6. Arrival time of peak discharge for various villages and towns.

86°0'E

85°40'E

iendshin Bridge

86°20'E

4.2. Hazard Map

We divided hazard into four levels based on the natural Jenks classification method of ArcGIS, namely low, middle, high, and very high hazard. The hazard level is generally high or very high in the river course, since our hazard index measures susceptibility to GLOF damage and the extent of such damage. In Dajie village and its downstream area, GLOFs from Gangxico, Cawuqudenco, Beihu, and Taraco threaten safety. For example, Jiangdong Primary School and some buildings are located near the river course where they are exposed to high hazard (Figure 7). The upper main district of Nyalam near the river course is also exposed to high and very high hazard (Figure 8). Hence, future development of the region should proceed cautiously.

0.5

0.0

0

5

Zhangzangbu Bridge

15

20

25

10



Figure 7. GLOF hazard levels along the upper Poiqu River, around the (**a**) Jiangdong Bridge, and (**b**) Jianggang village.



Figure 8. GLOF hazard levels in (**a**) Nyalam County and (**b**,**c**) along the river. (**b**) View upstream and (**c**) view downstream.

5. Discussion

5.1. Uncertainty Analysis

5.1.1. Clear-Water Flow

Although most GLOFs can evolve into debris flow [59], we only conducted clear-water flow simulations in this study for three reasons. First, debris flow simulation requires more parameters, which are lacking in this study. In our GLOF modeling, we either applied empirical equations to obtain parameters or avoided using complicated parameters that can only be obtained through field investigation [31,34,52,53]. Second, the clear water flow scenario in the HEC-RAS model is easy to apply and can give first-order results that improve the capability of practitioners to learn more about glacial lake hazard/risk assessment. Third, debris flow causes more severe damage near the breach, while clearwater flow can move farther distances and inundate more areas, which is more suitable for maximizing the scope of assessment [60].

5.1.2. Comparison with Other Studies

The overall behavior of GLOFs in the valley was well demonstrated based on HMA DEM (8 m). Although using HMA DEM in steep, narrow topography involves higher uncertainty than in flatter areas, it had little impact on our simulation results. Due to data limitations, we only analyzed simulation results in the Chinese part of the Poiqu River basin, which has relatively flat valleys. Moreover, the uncertainty of HMA DEM is equivalent to other DEMs, including SRTM (90 m), TanDEM-X (90 m), and PALSAR-DEM (12.5 m) (Niipele and Chen, 2019). A comparative experiment performed on these DEMs in the Nianchu River basin, Eastern Himalayas [33], indicated that the ratios of 100 random points extracted from different DEMs are close to 1:1 (the average difference is less than 3 m), and the median is less than 2 m in pairwise comparisons. In addition, we reconstructed the 1981 Cirenmaco GLOF to verify the credibility of HMA DEM, utilizing the same method as Wang et al. (2018) [31], which used STRM to model flood propagation. By comparison with in-situ measured data in six selected locations (Table 6) [42], uncertainties in the floods reconstructed by HMA DEM and STRM were analogous, and both were within 30% difference of in-situ measurements. Moreover, the presented flood characteristics are also analogous since the average flood depth was estimated to be 15.33 m and 14.21 m using STRM and HMA DEM simulations, respectively. Modeling with HMA DEM not only guarantees the reliability of model results compared with other lower-resolution DEMs, but also has better capacity to display details. This helps improve the accuracy of the modeling output and the subsequent hazard assessment.

Table 6. Reconstructed water depth at selected locations compared with observations and previous studies.

Locations	Distance from the	Maxim	num Water Depth(m)	
Locations	Lake Outlet (km)	Xu (1988)	Wang et al. (2018) SRTM	This Study HMA, 8 m
Zhangzangbo Bridge	6.4	18.5	23.8(28.6%)	19.7(6.5%)
Friendship Bridge	19.5	17.4	22.3(28.2%)	25.3(45.4%)
Phulpin Bridge	25.1	12.5	13.7(9.6%)	15.2(21.6%
K103 Bridge	29.5	22.9	19.1(-16.6%)	23.2(1.3%)
K94 Bridge	38.9	6.9	5.9(-14.5%)	6.7(-2.9%)
Bharabise Bridge	46.5	6.0	6.2(3.3%)	4.4(-26.7%)

5.1.3. Modeling Parameters

Lake volume, peak discharge, and outburst duration were estimated via empirical method, which inherently introduces uncertainty. The Cirenmaco volume was observed to be 18×10^6 m³ during a bathymetric survey in 2012 [31], which is larger than the estimation based on Equation (1) (11.24 × 10⁶ m³). Khanal et al. (2015) [36] similarly estimated the Cirenmaco volume and their result (12×10^6 m³), using a different formula, is very close to ours. Compared with other empirical formulas [61–63], Equation (1) is more suitable for some large or medium-sized moraine-dammed lakes that have little ice in the moraine dam and lake bottom [54]. In addition, some differences in evolution exist between Cirenmaco and the other six glacial lakes. Based on previous remote sensing images, the other six lakes likely developed in original moraine depressions. However, Cirenmaco was originally similar to a hot molten lake that gradually expanded through the continuous melting of ice at the bottom (Figure 9); its maximum depth measured in 2012 was approximately 130 m. This may be one of the most important reasons for the difference between measured data and estimated data for the Cirenmaco water volume.



Figure 9. An example of the differences in lake evolution between (a,b) Cirenmaco and (c,d) Beihu and Taraco.

5.2. Paradigm for Mapping Hazard/Risk

Due to the destructive impact of GLOFs on downstream areas, mitigating these risks has become a focus of GLOF research. Timely and effective assessment mapping is important in understanding GLOF propagation. Such mapping plays a significant role in downstream land use and urban planning, as well as in the application of prevention measures. However, some models cannot be freely downloaded or are difficult to use in the simulating process. As a result, practitioners' efforts to learn more about glacial hazard/risk have been hampered. In this study, we aimed not only to assess future GLOF hazard/risk in the Poiqu River basin, but also to provide a paradigm for hazard assessment and risk management that uses an easier method, thus enabling broader application (Figure 10). Most of the data can be collected through free channels. The main processes are as follows:

- Determine the potentially dangerous glacial lakes (PDGLs). This step can be based on previous studies, e.g., Kougkoulos et al. (2018) [64] and Allen et al. (2019) [26], which have established an inventory of PDGLs.
- Prepare the data and model. The HEC-RAS model is recommended due to its free availability (https://www.hec.usace.army.mil/software/hec-ras/, accessed on 15 October 2019), ease of operation, and extensive applications. Data from DEM is a critical component in flood simulation. When any other high-resolution DEM is not available, STRM can be used because of its better accuracy and wide range of applications. The data for infrastructure or farmland may be extracted from the most recent Landsat/Sentinel-2 images or from Google Earth.
- Estimate GLOF parameters. In the absence of in-situ measured data, lake volume and peak discharge may be determined by empirical or statistical methods. For example, a model-based Bayesian was presented by [65], which utilized robust linear regression to estimate parameters. A dam-breach hydrograph may be inferred using the same method as this study or may be simulated using a 1D breach model [33,36].

 Map hazard/risk. The flood depth and velocity datasets from the HEC-RAS model can be combined with the hazard/risk index and possible lake drainage scenarios to draw a synthesized map. These datasets can also be using to make a detailed assessment of exposure for downstream infrastructure, farmland, and population.



Figure 10. A paradigm for mapping GLOF hazard/risk.

5.3. Lessons for GLOF Management

The Poiqu River basin is severely threatened by GLOFs. A large number of high and very high-risk glacial lakes and their transboundary threats have made the region a great concern in the past few decades. This study fully demonstrated the GLOF path, depth, and velocity, as well as the arrival time of peak discharge for various villages and towns in different outburst scenarios; revealed the exposure of communities and infrastructure to the flood path; and provided a hazard map. These are of great significance not only for future development planning of the region, but also for hazard and risk assessment of glacial lakes in many regions. At present, sporadic detailed risk assessment for downstream communities of glacial lakes in the Himalayas has been conducted. Thus, integrated study of this area to respond to the threat of GLOFs is needed. The paradigm presented in this study will help more scholars to carry out hazard and risk assessment of glacial lakes.

6. Conclusions

We performed GLOF modeling using the 2D capabilities of HEC-RAS. The overall behavior of GLOFs in the Poiqu River basin was well simulated. Seven very high-risk moraine-dammed lake outbursts with different drainage percentage are presented, and the assessment of multiple GLOF hazards is provided. Meanwhile, we present a paradigm for practitioners to manage the hazard/risk caused by GLOFs.

Our results reveal that when any glacial lake drains completely or partly, most of the flooding will enter Nepal and continue to cause damage after raging in China. Galongco and Jialongco in the upper reaches of Nyalam can threaten infrastructure near the river course. Hence, we should be cautious about future development near the riverside. In total, there are 57.5 km of highways, 754 buildings, 3.3 km² of farmland, and 25 bridges that may be threatened by GLOFs, with the affected area exceeding 45 km² in the Chinese part of the Poiqu River basin. Villages and towns downstream from moraine-dammed lakes, except for Ere village, have more than 30 minutes to evacuate as long as early warning systems operate in a timely manner. Appropriate and effective measures should be used to adapt to GLOF hazards and promote the sustainable development of mountainous regions.

Author Contributions: Conceptualization, T.Z. and W.W., methodology, T.Z., supervision, W.W., and B.A., writing—original draft preparation, T.Z.; writing—review and editing, W.W., T.G., B.A. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the National Natural Science Foundation of China (Grant No. 41771088), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20100300), and the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (2019QZKK0208).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No supplementary materials.

Acknowledgments: We are grateful to the valuable comments and suggestions from Guoqing Zhang and Yanbin Lei.

Conflicts of Interest: The authors declare there no conflict of interest.

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