A glacial lake outburst flood risk assessment for the Phochhu River Basin, Bhutan

Tandin Wangchuk[1, 2], Ryota Tsubaki[2]

[1]National Center for Hydrology and Meteorology, Bhutan
[2]Department of Civil and Environmental Engineering, Nagoya University, Japan

Correspondence to: Ryota Tsubaki (rtsubaki@civil.nagoya-u.ac.jp)

Abstract. The melting of glaciers has led to an unprecedented increase in the number and size of glacial lakes, particularly in the Himalayan region. A Glacial Lake Outburst Flood (GLOF) is a natural hazard in which water from a glacial or glacier-fed lake is swiftly discharged. GLOFs can significantly harm life, infrastructure, and settlements located downstream, and can cause considerable ecological, economic, and social impacts. Based on a dam breach model, BREACH, and a hydrodynamic model, HEC-RAS, we examined the potential consequences of a GLOF originating from the Thorthomi glacial lake, located within the Phochhu River Basin, one of Bhutan's largest and rapidly expanding glacial lakes. Our analysis revealed that, following a breach, the Thorthomi glacial lake will likely generate a peak flow of 16,360 $m^3 s^{-1}$ within four hours. Such discharge could potentially cause considerable damage, with an estimated 245 hectares of agricultural land and over 1,277 buildings at risk of inundation. To mitigate ecological, economic, and social impacts on downstream areas, our results emphasize an urgent need for understanding and preparing for the potential consequences of a GLOF from Thorthomi Lake. Our findings provide valuable insights for policymakers and stakeholders involved in disaster management and preparedness.

1. Introduction

1.1. Glacial lakes and outburst floods

Floods are one of the most common natural disasters worldwide and can cause extensive socio-economic damage. Globally, over the last two decades, floods have affected approximately 2.3 billion people and caused an estimated 622 billion (USD) in damage (UNISDR, 2014). Glacial Lake Outburst Floods (GLOFs) are floods caused by sudden water release from glacial or glacier-fed lakes, and cause a rapid rise in water level over a short time in downstream areas, resulting in devastating consequences (Gurung et al., 2017; Komori et al., 2012; Taylor et al, 2023). GLOFs are infrequent but highly destructive natural disasters that are difficult to predict. Prior to their occurrence, the extent of damage is also difficult to predict. Over the past few decades, the acceleration of glacier melting and recession, primarily driven by climate change, has led to a significant increase in the number of moraine-dammed (natural dams formed by glacial processes) glacial lakes (Sattar et al., 2021; Westoby et al., 2014; Worni et al., 2014). Due to climate warming (Gardelle et al., 2011), the Eastern Himalayan area, in particular, has seen a significant increase in the number and area of glacial lakes, thereby increasing the vulnerability of nearby communities to potential GLOF impacts (Hagg et al., 2021). Taylor et al. (2023) estimated that approximately 15 million people are exposed to risks associated with potential GLOFs and that most of these populations are concentrated within High Mountain Asian (HMA) areas.

Although GLOF research and studies have gained global momentum in recent years, only a few studies have been performed in Bhutan. Numerous studies conducted in Nepal and China have simulated and assessed GLOF risks. Still, detailed studies on Bhutan's exposure to GLOF-related hazards are scarce. Such scarcity can be attributed to a lack of required field data, as well as to Bhutan's limited exposure to the global scientific community.

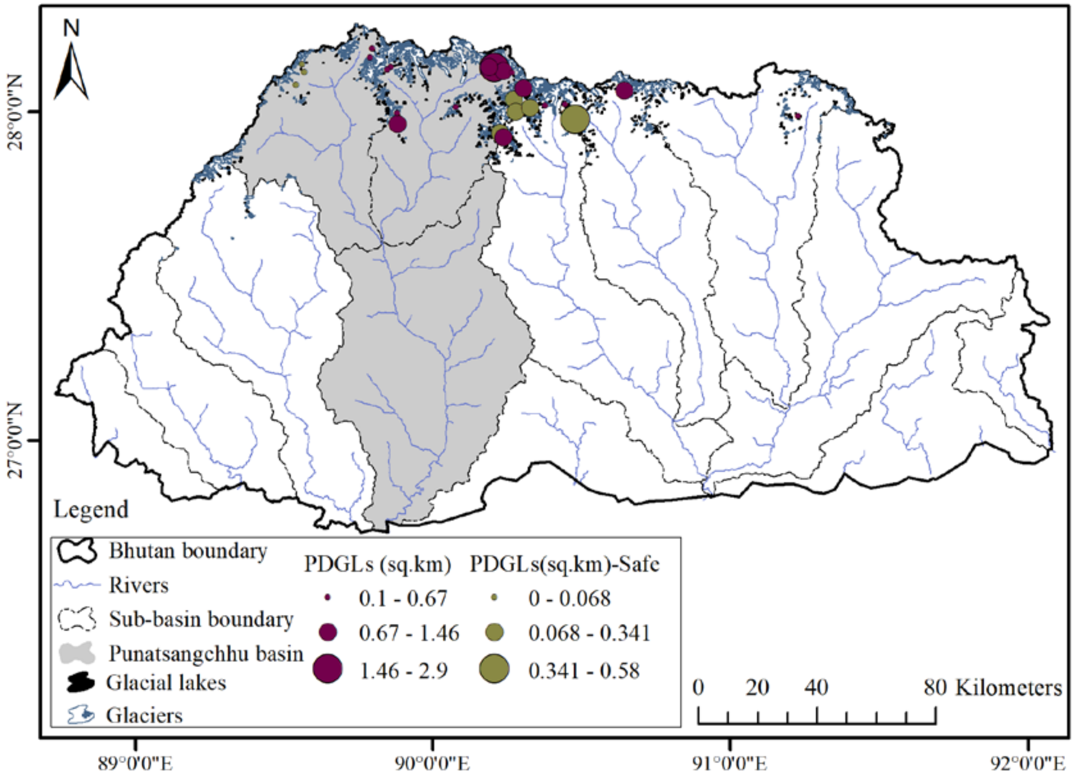

Figure 1. A map showing the rivers and basin system of Bhutan, as well as the distribution of potentially dangerous glacial lakes. Bubbles are scaled to total lake area and color-coded for classification. Data source: National Center for Hydrology and Meteorology (NCHM).

1.2. Past GLOF events in Bhutan

In the past, Bhutan has faced several GLOF events. However, many of these events were either not reported or not documented. One of the most catastrophic GLOFs took place on 6 October 1994, when the moraine dam of Luggye Lake partially collapsed, leading to the release of a massive amount of water and debris downstream, destruction to infrastructure and farmland, and the death of 21 people (Watanabe and Rothacher, 1996; Leber et al. 2000). Another significant GLOF occurred in 2009, when an outburst from Tshojo Lake, located at the headwaters of the Phochhu River, caused downstream flooding. Based on satellite imagery, and a sedimentological and geomorphological analysis, Komori et al. (2012) attributed an outburst from the supra glacial lake on the Tshojo Glacier to the event. The most recent GLOF took place on 28 July 2015, when the Lemthang Tsho outburst, discussed by Gurung et al. (2017), released an estimated 0.37 million m^3 of water downstream and heavy rainfall triggered the event.

1.3. Potentially dangerous glacial lakes in Bhutan

Based on the latest report from the National Center for Hydrology and Meteorology (NCHM) in Bhutan, 567 glacial lakes in the country span an area of 55.04 km^2, accounting for 19.03% of total water bodies (NCHM, 2021). In 2001, the Department of Geology and Mines (DGM) in Bhutan and the International Center for Integrated Mountain Development (ICIMOD) performed the first-ever inventory of glaciers, glacial lakes, and Potentially Dangerous Glacial Lakes (PDGLs); and identified 24 glacial lakes that fit this category (Mool et al., 2001). However, in 2019, using field-verified data and the latest Sentinel 2 satellite images, NCHM reassessed the number of PDGLs and revised the number to 25, with eight lakes now considered to be safe based on lake morphology, surrounding features, bathymetry conditions, and associated feeding glaciers (NCHM, 2019b). Figure 1 provides a map of rivers and the river basin system within Bhutan, together with the distribution of glaciers and glacial lakes. The Punatsangchhu River Basin contains eleven PDGLs (the largest in the country). The Phochhu sub-basin contains nine PDGLs, making it a hotspot for GLOFs and glacial related disasters.

Warming climate exacerbates the hazards of GLOFs. Since such risk will only intensify in the coming years, there is an urgent need for a comprehensive GLOF assessment. Therefore, a study assessing hazards associated with glacial lakes and GLOFs is crucial for understanding hazards, as well as their subsequent impacts on hydrological and socio-economic aspects within the Punatsangchhu River Basin.

1.4. Increasing concern regarding a Thorthomi GLOF

Thorthomi Lake is the largest of nine potentially hazardous glacial lakes located within the Phochhu Basin. Due to the significant potential risk posed to downstream settlements resulting from a GLOF, Thorthomi glacial lake has become a serious concern because of the following factors: (1) rapid expansion of the Thorthomi supra glacial lake, (2) the size of glaciers and probable future lake size, (3) the weakened left lateral moraine of the lake due to the 1994 Luggye GLOF, (4) active sliding on the moraine wall separating the Thorthomi and Rapstreng Lakes, (5) seepage from the lake, and (6) rock and snow avalanches, as summarised by Karma (2013). To address these factors, the government of Bhutan initiated a high-priority project, referred to as the National Adaptation Plan of Action (NAPA), under the United Nations Framework Convention on

Climate Change (UNFCCC) funding scheme in 2006. The project sought to reduce the GLOF risk potential from Thorthomi Lake and involved lowering the lake's water level over four years, resulting in a reduction of 3.68 metres. However, due to challenging working conditions and health issues, the project fell 1.32 metres short of its target, although approximately 17 million m^3 of lake water was artificially released. The project additionally included setting up a GLOF Early Warning System along the Punakha-Wangdue Valley for alerting residents in the event of a GLOF.

1.5. Uncertainty in GLOF bathymetry

The volume and geometry of the glacial lake are regulating factors of the glacial lake outburst process. Glacial lakes are generally formed from a depression left behind by retreating glaciers, which, in most cases, are produced when a moraine is filled with melt water. Depending on geomorphology, the presence of sediment, and glacial over-deepening capacity, formed glacial lakes can manifest specific lake bathymetry and influence glacial hydrology (Cook and Swift, 2012). Due to remote locations and high elevations, accessing and conducting field surveys to map glacial lake bathymetry is challenging.

Despite challenges, measurements of lake bathymetry are crucial for determining a lake's volume and surface area, and are necessary for assessing potential flood volumes and the risk of GLOFs. In 2019, the National Centre for Hydrology and Meteorology (NCHM) conducted bathymetric surveys in 14 of the 25 identified potentially dangerous glacial lakes, and mapped their maximum depth and volume. However, even though Thorthomi glacial lake is considered to be a critical lake that could burst in the future, due to the difficulty associated with conducting a survey, the bathymetry of Thorthomi glacial lake remains unknown. Since lake geometry is a crucial parameter for dam breach modelling and subsequent hydraulic routing, lake depth and volume needed to be estimated.

1.6. The focus of our study

We evaluated the potential risk of a GLOF from Thorthomi Lake. The physically based mathematical dam breach model, BREACH, was used to simulate a glacial lake dam breach and was coupled with HEC-RAS to route the flood wave propagating downstream. We sought to simulate both the spatial extent and the lead time of flood wave arrival at several locations along the river. Prior to predicting Thorthomi GLOF hazards and potential risks, we reconstructed the 1994 Luggye GLOF event to validate the dam breach model and the flood wave routing model, which included river topography and roughness.

Our study is one of a few studies that has simulated probable floods from Thorthomi Lake, and that has estimated inundation extent and flood arrival times within a scientific setting. Such studies form an essential basis for flood risk assessments, early warning system (EWS) installation, economic planning, countermeasure planning, design, and stakeholder education and awareness programs. Since the overtopping of lake water is the major failure mode (Awal et al., 2010; Begam et al., 2018; Neupane et al., 2019), our study assumed that GLOFs are triggered by the overtopping of lake water.

The main components of our study are as follows:

1) estimating the geometry and water volume of Thorthomi Lake using available glacial lake geometry data;
2) estimating the potential outburst flood hydrograph using a dam breach model, BREACH, with available physical parameters, and;
3) assessing Thorthomi GLOF hazards and potential risks using a 2D hydraulic model.

1.7. Structure of the paper

The paper contains six sections. Section 1 introduces the overall concept of a GLOF, and provides information obtained from previous studies and information related to GLOFs in the context of Bhutan. Section 2 describes the area of the study and the GLOF event to be used for model validation and calibration. Section 3 describes materials and methods of the study. A schematic diagram showing input data, used models/methods, and outputs is provided in Figure 2. Section 4 reports obtained results. Section 5 discusses the consequences of a Thorthomi GLOF. A conclusion is presented in Section 6.

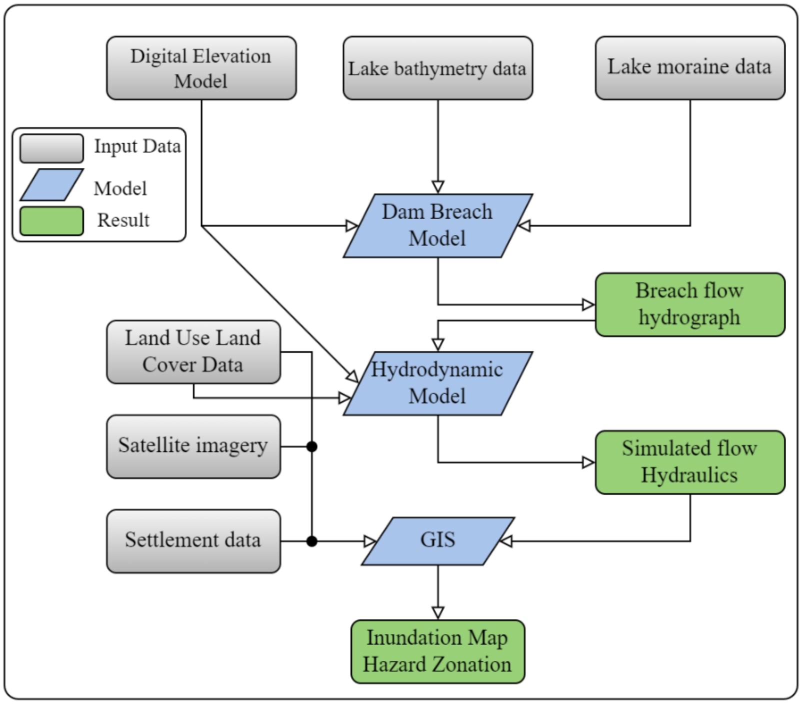

Figure 2. A schematic diagram of the methodology employed in our study. Input data used for the study are indicated with grey boxes, models are indicated with blue boxes, and results are indicated with green boxes.

2. Study area and GLOF event

2.1. The Punatsangchhu River Basin

We assessed flood risk for the Phochhu catchment, within the Punatsangchhu River Basin (PRB), caused by a GLOF from Thorthomi Lake. The basin, located within the central portion of Bhutan (Figure 3 (a)), is one of the largest basins in Bhutan, spanning an approximate area of 9,760 km^2; and is drained by the Phochhu and Mochhu Rivers (Figure 3(a)) to the Indian plains. The PRB consists of five districts: the Gasa, the Punakha, the Wangdue Phodrang, the Dagana, and the Tsirang, spanning approximately 25% of the total area of the country (38,394 km^2). These districts constitute 16.6% (735,533) of the total population of Bhutan (NSB, 2018). The annual averaged discharge of the basin ranges from 194 to 374 m^{3}s^{-1}, with the highest recorded discharge of 2,654 m^{3}s^{-1}, observed at the WangdiRapid station (location shown in Figure 3(c)), occurring in 2009 during Cyclone Aila.

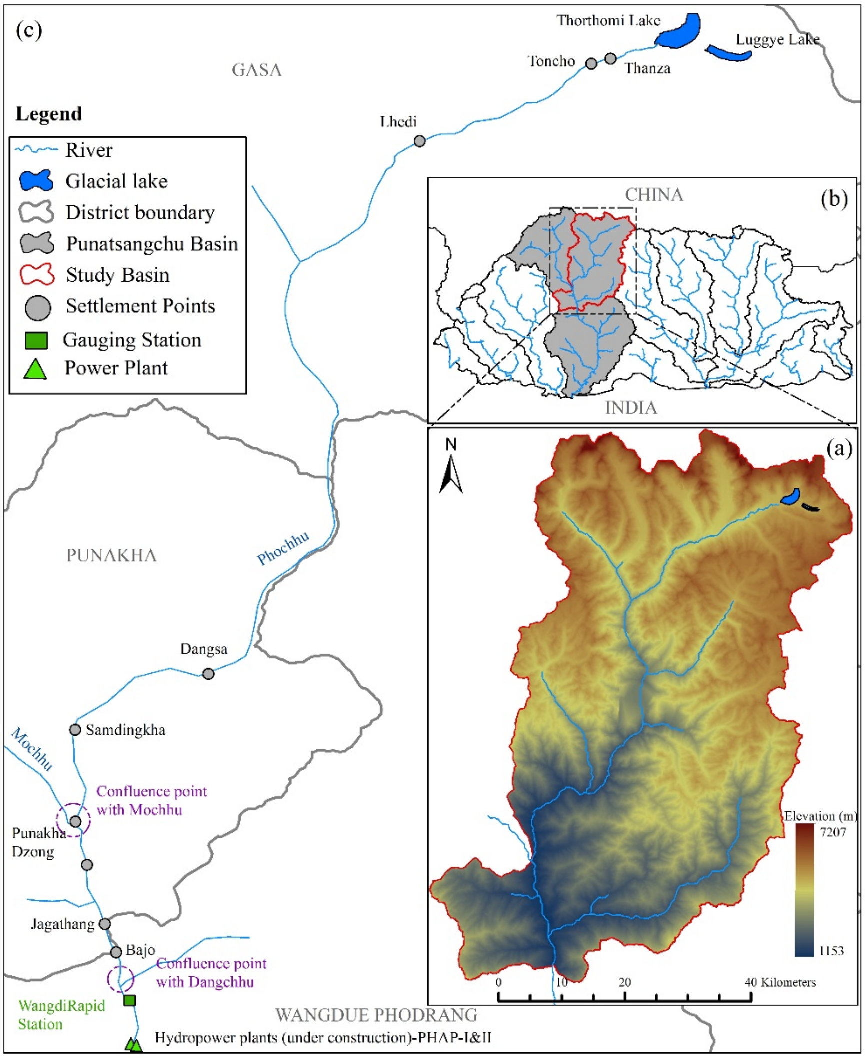

Figure 3. Map of the study area. (a) A Bhutan map showing rivers and river basins. (b) The elevation distribution of the study area. (c) The Phochhu River and major settlement points along the river.

The PRB is home to eleven (11) potentially dangerous glacial lakes. Nine (9) of these lakes lie within the Phochhu sub-basin. The Thorthomi glacial lake has an area of 4.3 km^2 (NCHM, 2019b), is located at the headwater of the Phochhu sub-basin at over 4,440 meters above sea level, and is considered to be one of the most dynamic and dangerous glacial lakes within Bhutan. The Phochhu River, one of the main tributaries of the Punatsangchhu River, originates from the high mountains of Lunana, in northern Bhutan, and flows some 90 kilometres downstream, where it joins Mochhu at Punakha Dzong (monastery) (Figure 3 (c)), and flows from this area as the Punatsangchhu River.

2.2. Thorthomi glacial lake

The Thorthomi glacial lake is widely recognized as the likely consequence of climate warming and, since feeding glaciers terminating in the lake rapidly melt, is expanding each year. Based on a comprehensive analysis of cryospheric, geotechnical, and geomorphological factors, Rinzin et al. (2023) concluded that Thorthomi Lake is highly susceptible to GLOF events.

The Punakha and Wangdue Phodrang districts (Figure 3) within the Punatsangchhu River Basin (PRB) are renowned as Bhutan's primary rice production regions, contributing 16% and 11%, respectively, to the nation's total rice output (NSB, 2021). The area is also rich in historical and cultural heritage, with notable landmarks such as Punakha Dzong, which served as the former capital of Bhutan. Fertile flood plains are located on the banks of the Phochhu and Punatsangchhu Rivers, and the region encompasses settlements such as Samdingkha and Jagathang, together with major towns such as Khuruthang and Bajo. The floodplain of the Punatsangchhu River accommodates these settlements, while downstream, approximately 115 kilometres away from Thorthomi Lake, two significant hydropower plants, the Punatsangchhu Hydroelectric Project Authority - PHPA-I and II, are currently under construction (see the bottom of Figure 3(c) for locations of the two hydropower plants.) Given the exposure of critical infrastructure and settlements to potential GLOFs from the lake, an assessment of hazards within this area is of paramount importance.

2.3. The 1994 Luggye GLOF

Luggye glacial lake is one of the potentially dangerous glacial lakes in Lunana, Bhutan's northern region. As shown in Figure 4, the lake is one of four glacial lakes in an area that spans a few kilometres and had an outburst in 1994. Although there is no detailed official documentation on the GLOF at Luggye glacial lake, reports and articles describing the event do exist (e.g., Koike and Takenaka, 2012; Meyer et al., 2006; Richardson and Reynolds, 2000; Watanabe and Rothacher, 1996). The event was also documented in a technical report (Leber et al., 2000), when the Royal Government of Bhutan launched a major investigative project in 2000 to study the cause of the event.

The 1994 GLOF was a cascading phenomenon, where sudden drainage of the upstream Druk Chung glacial lake (see Figure 4) into Luggye Lake increased hydrostatic pressure on the moraine dam of Luggye Lake, releasing 18 million m^3 of flood water (Leber et al., 2000). The GLOF claimed the lives of 21 people, and inflicted major damage to infrastructure and downstream settlements; notably, the Punakha Dzong (monastery) suffered significant damage, although it is located 93 kilometres downstream from the lake (Richardson and Reynolds, 2000; Watanabe and Rothacher, 1996). During this period, a peak flow rate of 2,539 $m^3\,s^{-1}$ was observed at the WangdiRapid gauging station, located 15 kilometres downstream of Punakha Dzong (see Figure 3) and approximately 108 kilometres downstream of the flood source (data from NCHM.) Here, small contributions from the Mochhu (96 m^3/s on 7th October 1994) and Dangchhu basins (no gauging station in the basin), as well as other small tributaries, affected the peak flow rate.

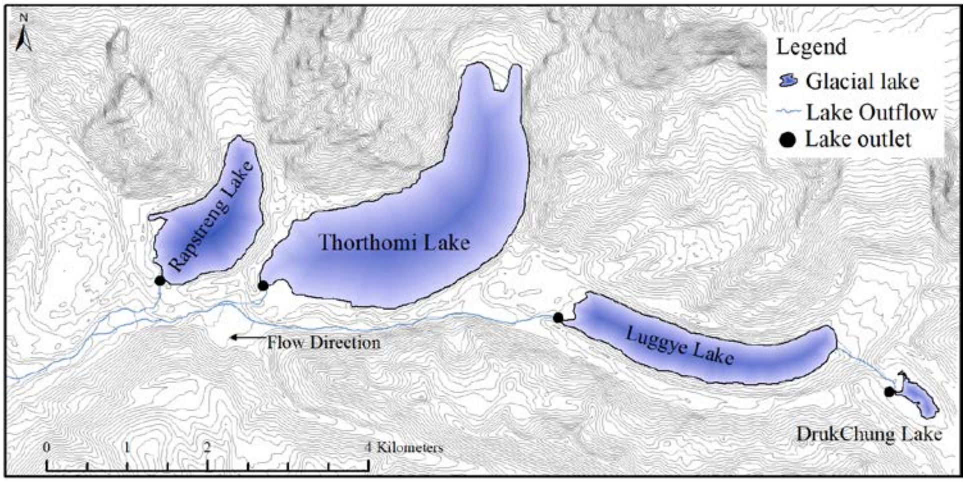

Figure 4. Four glacial lakes within the Lunana region (the Lunana Complex).

To estimate the breach outflow hydrograph, several studies have attempted to reconstruct the 1994 Luggye GLOF event (e.g., JICA, 2001; Koike and Takenaka, 2012; Meyer et al., 2006). Koike and Takenaka (2012) estimated that peak discharge from the Luggye Lake breach ranged from 1,800 to 2,500 m^3s^{-1}, depending on inflow conditions measured by Yamada et al. (2004). We reconstructed the 1994 GLOF event to verify (1) the BREACH model, (2) DSM error correction methods, and (3) Manning's coefficient, which were used to predict the potential risk caused by a Thorthomi GLOF.

3. Materials and methods

3.1. Regression analysis for the lake geometry estimation

Estimating the potential flood volume of a glacial lake is critical for determining the magnitude of a GLOF. However, due to the challenging and inaccessible environments in which glacial lakes are often located, bathymetry data, which is necessary for calculating lake volume, including for Thorthomi Lake, is scarce. Although several literature estimates of Thorthomi Lake volume are available (Karma, 2013; Singh, 2009), no details on how volumes were estimated have been documented. Maximum lake depth and volume for Lake Thorthomi were estimated based on the parametric relationship proposed by Sakai (2012).

To address data scarcity for glacial lake geometries, various studies have proposed methods for estimating glacial lake depth and volume based on other, more accessible, parameters such as lake area (Cook and Quincey, 2015; Huggel et al., 2002; O'Connor et al., 2001; Sakai, 2012), as well as depression angle from the lakeshore (Fujita et al., 2013), and surrounding topography (Heathcote et al., 2015). Empirical relationships such as area-volume and area-depth are useful for estimating a lake's depth and potential flood volume. Cook and Quincey (2015) refined the area-volume relationship proposed by Huggel et al. (2002) by increasing sample size and removing duplicate sample data. They also classified the predictability of lake volume and depth based on regions and lake types, and determined that predictability is influenced by a lake's origin and evolution. The relationship proposed by Cook and Quincey (2015) is based on 45 data points, including the data points used by Huggel et al. (2002) for removing duplicate data, and takes the following form:

$$D_{\mathrm{mean}} = 0.1697\, A^{0.3778}, \tag{1}$$

where D_{mean} is the mean depth (in metres) and A is the area (in square metres). The volume-area relationship (V, volume in cubic metres) can be derived by multiplying the area of both sides, as follows:

$$V = 0.1697\, A^{1.3778}. \tag{2}$$

A similar approach was proposed by Sakai (2012), where maximum depth was taken into consideration rather than mean depth. The bathymetric measurement data of 17 glacial lakes (15 moraine-dammed glacial lakes and 2 thermokarst lakes) from Bhutan, Nepal, and Tibet were used to derive an area-maximum, depth-volume relationship, so estimations of depth and volume from the area of glacial lakes could be determined (Sakai, 2012). The regression equation took the following form:

$$D_{\mathrm{max}} = 95.665\, A^{0.489}, \tag{3}$$

where D_{max} is maximum depth (in metres), A is area (in square kilometres), and the volume-area relationship (V, volume in million m^3) takes the following form:

$$V = 43.24\, A^{1.5307}. \tag{4}$$

Unlike previous studies (e.g., Cook and Quincey, 2015; Fujita et al., 2013; Huggel et al., 2002; O'Connor et al., 2001), mean depth is estimated, which is straightforward for estimating volume, Equation (3) estimates maximum depth. To estimate the maximum depth and volume of Thorthomi glacial lake, we employed the equations proposed by Sakai (2012). The equations allow the independent calculation of maximum depth and volume. As conceptualised by Cook and Quincey (2015), bathymetry of the lake was estimated based on the idea of idealised geometric shape. The lake bottom was also assumed to follow an elliptical shape, as commonly observed in most moraine-dammed glacial lakes in Bhutan.

3.2. The moraine dam breach and its modelling

3.2.1. Previous studies

GLOFs are triggered by a breach in a moraine dam that holds the lake in place and are caused by an external triggering event. While the structure of the dam itself is an important factor, destabilisation of a dam due to a trigger event is the primary cause of a breach.

To estimate potential flood flow resulting from a dam breach and associated hazards, several studies have simulated dam breach floods using dam breach models (Bajracharya et al., 2007; Hagg et al., 2021; Huggel et al., 2002; Koike and Takenaka, 2012; Maskey et al., 2020; Meyer et al., 2006; Shahrim and Ros, 2020; Wang et al., 2008; Worni et al., 2014). BREACH is a numerical model describing the dam breach process and the resulting outflow hydrograph. The model is based on fundamental principles of hydraulics, sediment transport, soil mechanics, and the physical properties of dam materials and the reservoir. The model is physically based and was designed to predict the size, shape, and time of formation of a breach in a dam, as well as the resulting flow rate and the volume of water released. The BREACH model has been widely used in studies of dam breach flood hazards and risk assessments (Fread, 1988).

Koike and Takenaka (2012) used the BREACH model coupled with the flood flow model, FLO-2D, to perform a scenario analysis on the risks of a GLOF on the Mangdechhu River Basin, due to an outburst of the Metatshota glacial lake in Bhutan. The study concluded that although the breaching potential of the lake is low due to the wide crest and gentle slope of the moraine dam, a GLOF would affect several houses and farmland located on the flood plain (Koike and Takenaka, 2012). Hagg et al. (2021) performed a GLOF hazard assessment within the Mochhu Basin in Bhutan using the HEC-RAS dam break module, simulating a dam breach of the Shintaphu glacial lake, and concluded that risk is comparably small.

Our study used BREACH for describing the dam breach process for target lakes. Unlike parametric models, physically based breach models consider the geotechnical aspects of dam materials, as well as hydraulic and sediment transport (Fread, 1988; Maskey et al., 2020; Worni et al., 2014), which increases the predictive accuracy of future GLOF processes. The dam is assumed to breach due to overtopping flow resulting from a trigger event, such as an ice calving/avalanche or a rock avalanche. Most of the geotechnical properties of dam materials required as an input parameter are available in the report published by the National Center for Hydrology and Meteorology (NCHM, 2019a). A few properties were published by Koike and Takenaka, (2012). Some unavailable data was estimated by referring to previous studies.

3.2.2. Reconstruction of the 1994 Luggye GLOF dam breach

For reconstruction of the 1994 Luggye GLOF, the dam breach outflow hydrograph was estimated using BREACH (Fread, 1988). The bathymetry of Luggye Lake (Figure 5) and the material properties of the moraine dam (see Table 1) required for the model were based on various reports (NCHM, 2019a, 2019b). Topographic data of the moraine dam was derived from the Digital Surface Model (DSM). Since wave overtopping is a more common failure mode for moraine-dammed glacial lakes as compared to a piping failure (Neupane et al., 2019), to estimate breach outflow from Luggye Lake, overtopping failure of the moraine dam was assumed. The properties of moraine dam material have a significant effect on the growth of a breach (Maskey et al., 2020; Westoby et al., 2014). The mechanism in which the formation of a breach largely occurs determines the shape of the breach outflow hydrograph (Westoby et al., 2014). Therefore, gathering accurate in-situ data for reliable breach process reproduction is essential.

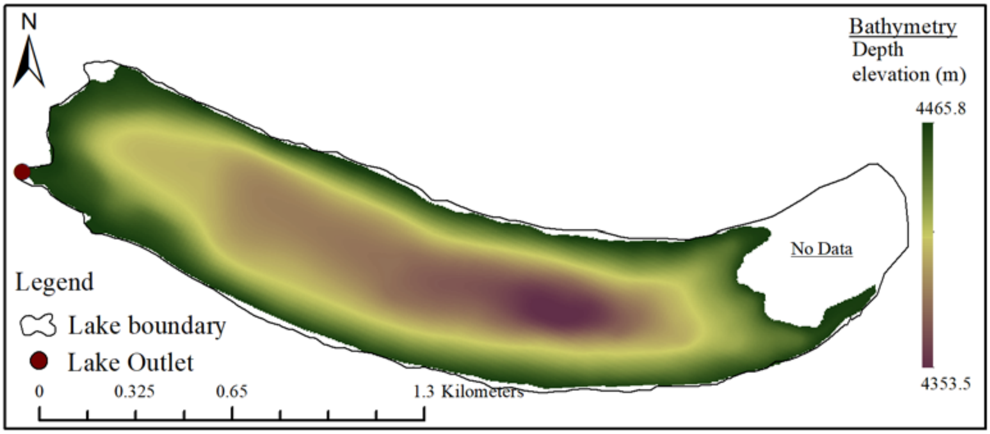

Figure 5. The bathymetry of Luggye Lake (data from NCHM).

Based on the estimation by Fujita et al. (2008), deduced from a combination of field measurements and remote sensing observations, the level of lake water was reduced 19 metres during the event. Table 1 provides moraine dam data and the moraine material properties of Luggye Lake used for the dam breach model. Parameters were either estimated or obtained from various available reports and research papers.

Table 1. Input parameters for the Luggye Lake BREACH model.

Moraine Dam Data		**Dam Material Properties**	
Surface area of the lake (km^2) [RSA]	1.46 [b]	Grain size (D_{50}) (mm)	1.362 [b]
Volume of water in the lake (mil. m^3), Eq. (4)	65.19 [b]	Porosity (%)	36.5 [c]
Maximum depth of the lake (m), Eq. (3)	96.93 [b]	Cohesive strength (kN m^{-2})	1.5 [b]
Top elevation of the dam (m) [HU]	4465 [a]	Internal friction (degree)	41 [b]
Toe elevation of the dam (m) [HL]	4370 [a]	Unit weight (kN m^{-3})	22.92 [b]
Slope of the upstream face of the dam (1: ZU)	1:4.8 [a]	Manning's coefficient (s m$^{-1/3}$)	0.07[b]
Slope of the downstream face of the dam (1: ZU)	1:6.5 [a]		

[a]Estimated in this study, [b]NCHM (2019a), and [c]Koike and Takenaka (2012).

3.2.3. The Thorthomi GLOF prediction

Breach initiation is assumed to occur due to an overtopping wave at the existing outlet (see Figure 4) induced by any probable triggering event. Moraine material properties and the topographic data of a moraine dam are either estimated from available terrain data or adopted from available reports and research documents. Table 2 provides moraine dam data and moraine material properties for Thorthomi Lake used in the BREACH model.

Table 2. Input parameters for the Thorthomi Lake BREACH model.

Moraine Dam Data		Dam Material Properties	
Surface area of the lake (km^2) [RSA]	4.3 [b]	Grain size (D_{50}) (mm)	2.01 [b]
Volume of water in the lake (mil. m^3), Eq. (4)	400 [a]	Porosity (%)	36.5 [c]
Maximum depth of the lake (m), Eq. (3)	161 [a]	Cohesive strength (kN m^{-2})	1.5 [b]
Top elevation of the dam (m) [HU]	4446 [a]	Internal friction (degree)	39 [b]
Toe elevation of the dam (m) [HL]	4370 [a]	Unit weight (kN m^{-3})	22.43 [b]
Slope of the upstream face of the dam (1: ZU)	1:6.2 [a]	Manning's coefficient (s m$^{-1/3}$)	0.07[b]
Slope of the downstream face of the dam (1: ZU)	1:6.3 [a]		

[a] Estimated in this study, [b] NCHM (2019a), [c] Koike and Takenaka (2012).

3.3. Flood routing

3.3.1. The hydrodynamic model

A hydrodynamic model is essential for understanding the characteristics of a flood wave caused by a GLOF propagating downstream, as well as for quantitatively evaluating the potential risks caused by a flood. To simulate the propagation of outflow from glacial lake breaches in Nepal, numerous studies, such as the Hydrologic Engineering Centre's-River Analysis System (HEC-RAS) used in Maskey et al. (2020), have employed various hydrodynamic models. Similar approaches that couple dam breach models to hydrodynamic models (e.g., Bajracharya et al., 2007; Koike and Takenaka, 2012; Westoby et al., 2015; Worni et al., 2014) have been performed for modelling the GLOF process chain in various regions.

Worni et al. (2014) provided a summary of various hydrodynamic models that have been used to model GLOFs. Discussed models include HEC-RAS, FLO-2D, BASEMENT, and Delft3D. The choice of a hydrodynamic model depends on factors such as the end objective, data availability, and the available budget. Each model has its own level of accuracy; however, the accuracy of results is primarily dependent on the precision of the elevation model, including channel geometry and floodplain topography. Errors in the elevation model can lead to inaccuracies in results (Casas et al., 2006; Xu et al., 2021).

The Hydrologic Engineering Centre's River Analysis System (HEC-RAS) is a commonly used hydrodynamic model that allows users to perform 1D and 2D steady/unsteady flow simulations (Brunner & CEIWR-HEC, 2016). We used the HEC-RAS to perform a 2D unsteady flow simulation of floods caused by a glacial lake dam breach. Since they represent spatially varied flood hydraulics (Horritt and Bates, 2001), the two-dimensional models employed are standard in flood modelling. In a 2D unsteady simulation, flow varies in time, along two spatial dimensions, and processes are predicted by the laws of conservation of mass (continuity) and the conservation of momentum for two horizontal directions. We used a full set of momentum equations (the shallow water equations) to simulate flooding as clear water flow. Although high viscosity and hyper-concentrated (sediment entrained) flows are inherent to the GLOF phenomenon (Clague and Evans, 2000; Vuichard and Zimmermann, 1987), to simplify modelling complexity and data requirements, most studies (Hagg et al., 2021; Koike and Takenaka, 2012; Maskey et al., 2020; Rinzin et al., 2023) have simulated GLOFs as clear water flow.

Other important considerations in hydrodynamic modelling are Manning's roughness coefficient and channel geometry. Both have significant impacts in predicting inundation extent and flow characteristics (Mosquera-Machado and Ahmad, 2007; Ye et al., 2018; Zhu et al., 2019). Hagg et al. (2021) demonstrated the influence of Manning's roughness coefficient for glacial lake outburst floods from the Shintaphu glacial lake in Mochhu Basin, Bhutan; and concluded that channel roughness is not essential for inundation extent but exerts a significant effect on flood velocity and flood arrival time.

3.3.2. The ground elevation distribution

3.3.2.1. Available data sources

The accuracy of hydrodynamic model results is heavily influenced by the quality of the elevation model used and is crucial for precise representation of the terrain for flood inundation modelling (Gyasi-Agyei et al., 1995; Yamazaki et al., 2014, 2017). Casas et al. (2006) demonstrated the effects of a topographic data source and resolution on flood peak discharge and the extent of inundation, and then concluded that laser-based elevation data is a suitable source for hydraulic modelling. Similarly, the influence of grid size on inundation propagation and water depth under varied topographical settings in 2D modelling has been demonstrated (Tsubaki and Kawahara, 2013). Both fine grid size representing main topographic features of the floodplain and accurate elevations at each grid point are essential for simulating flood flow with less uncertainty. Therefore, using the best available elevation model for the hydrodynamic simulation of floods is essential.

Since an accurate elevation model is essential for accurate hydrodynamic simulations, elevation models include error in varying degrees. To manage elevation error, various methods for correcting generic noise errors and bias have been proposed, and have been used in elevation models prior to running hydrodynamic/hydrological analyses. The Multi-Error-Removed Improved-Terrain (MERIT) Hydro DEM (see Figure 6 (c)) was developed based on SRTM and AW3D DEM. Water layer data at a 3-arc sec resolution (~90 m) was developed for river hydrology analyses at global, as well as at local, scales (Yamazaki et al., 2017, 2019).

Other bias-corrected elevation data, including the Forest And Building removed Copernicus DEM (FABDEM) (see Figure 6 (b)), developed from Copernicus DEM (COPDEM), where the height of trees and buildings are removed using machine learning, is also a preferable source for terrain data (Hawker et al., 2022).

The AW3D Digital Surface Model (DSM) was jointly developed by the Remote Sensing Technology Centre (RESTEC) and the NTT DATA Corporation, utilising PRISM data acquired by the Advanced Land Observing Satellite (ALOS) of the Japan Aerospace Exploration Agency (JAXA). Rough resolution DSMs are distributed by several organizations free of charge, however, for our study, we used the finer commercial DSM product, AW3D-2.5m, as the primary source of topography. The cell size of the DSM for the focus area was approximately 2.2 metres for both the *X* and *Y* directions, and was projected to WGS84-UTM-Zone 45N. The DSM was selected because it provided a finer terrain representation as compared to other freely available Digital Elevation Models (DEMs). Figure 6 illustrates the difference in terrain representation using three terrain data sources. The AW3D-2.5 m DSM represents topography, especially in the river valley and in the developed flood plain, much better than the other models.

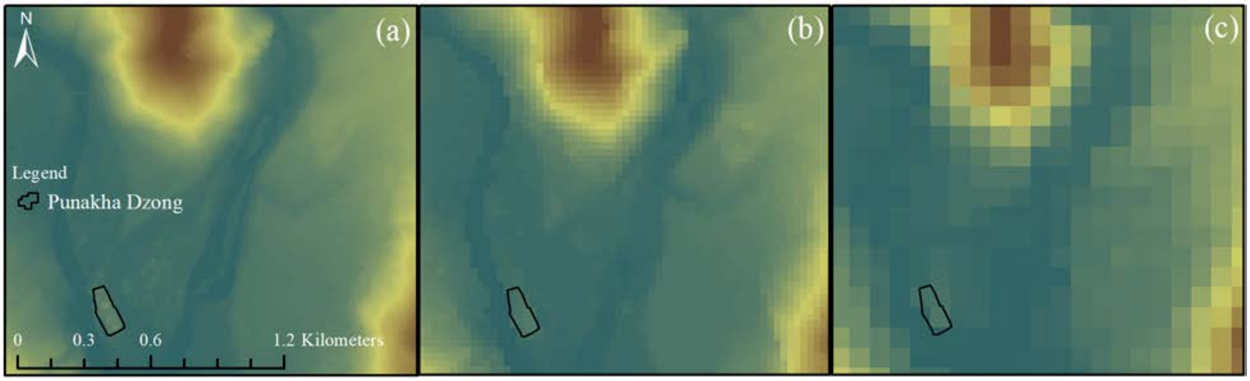

Figure 6. The Punakha Dzong region as represented by three different terrain models: (a) the AW3D-2.5 m DSM, (b) the FABDEM-30 m, and (c) the MERIT HydroDEM-90 m.

3.3.2.2. Elevation errors and their correction

Since the AW3D DSM was obtained using satellite photogrammetry, representations of the river bottom, especially in forested and deep gorge areas, are sometimes inaccurate. If we directly used topography in hydrodynamic modelling, the DSM covered structures along the river, as well as bridges crossing the river, disturbing flood flow. To avoid such anomalies in the elevation model and in the hydrodynamic simulation results, a river channel delineation was performed. The presence of spikes within the DSM, along the river’s path, can obstruct the downstream flow of floodwater, resulting in the formation of non-existent deep pools. One way to improve topography surrounding a river is the use of bathymetric survey data. However, no such survey has been conducted within the study area. To improve representation for the river channel, our study utilised a rule-based correction method.

The Agriculture Conservation and Planning Framework (ACPF) is a GIS-based tool developed by the United States Department of Agriculture (USDA) to identify areas with impeded water flow, and to improve hydrologic flow using flow direction and an accumulation analysis (Porter et al., 2016). While the ACPF is a valuable tool for hydrologic flow and watershed planning, it has limited applicability for terrain correction in hydrodynamic modelling because the ACPF does not allow users to define the bathymetry of a river channel.

Another widely used channel modification method is the in-built function of HEC-RAS. The Channel Design/Modification Editor tool is a module used to modify an unrealistic cross-section or to introduce a user-defined channel cross-section (Brunner, 2016). The tool effectively removes spikes in the elevation model along a river channel while maintaining the natural slope of the represented topography. The modified channel TIN (Triangulated Irregular Network) can be overlain on the original DSM and exported as a single raster file with modified features. Rinzin et al. (2023) applied the method to modify terrain and to delineate river flow paths for a GLOF simulation. For our study, we used this tool to condition the DSM in the middle region of the model domain, a forested deep gorge, where huge spikes were included within the elevation model. The modification was only applied to the channel section. The remaining portion was left as it was.

3.3.3. Hydrodynamic model for the 1994 Luggye GLOF reconstruction

Downstream propagation of the flood was simulated using the HEC-RAS model. The calculation domain was defined by the 2D flow area. The overall size of the flow area was 64 km^2. The domain was modelled using a 20-m-resolution computational grid, consisting of 157,188 computational cells, and solved with a time step of one second. The elevation of each grid cell was specified based on a 2.2 m, hydro-conditioned digital surface model (DSM, see Section 4.2.1), and Manning's *n* was set to 0.35, in the range provided by the HEC-RAS manual (Brunner, 2016). The dam breach outflow hydrograph obtained from the BREACH model was used as the upstream boundary; and normal depth, calculated based on downstream slopes derived from the DSM, was used as the downstream boundary condition.

3.3.4. The hydrodynamic model for future Thorthomi GLOF prediction

We used a hydrodynamic model almost that was similar to the model used for the 1994 Luggye GLOF reconstruction. The domain was a bit shortened because the Thorthomi glacial lake is located 2 km downstream of the Luggye glacial lake. The overall size of the flow area was 62 km^2. The domain was modelled using a 20-m-resolution computational grid consisting of 153,790 computational cells with a temporal resolution of one second.

4. Results

4.1. The 1994 Luggye GLOF reconstruction

4.1.1. Dam breach processes

As shown in Figure 7(a), simulated peak flow (*Qp*) of the dam breach outflow hydrograph was 6,030 $m^3 s^{-1}$, and 1.9 hours (~114 minutes) were required to reach peak flow (the time to peak, *Tp*). The volume of the GLOF and the reduction of lake water level due to the event were 21 million m^3 and 19 m, respectively, in agreement with the findings of Fujita et al. (2008) which was based on a combination of in situ observations and remote-sensing data. Dimensions for the estimated breach of the dam are provided in Figure 7(b).

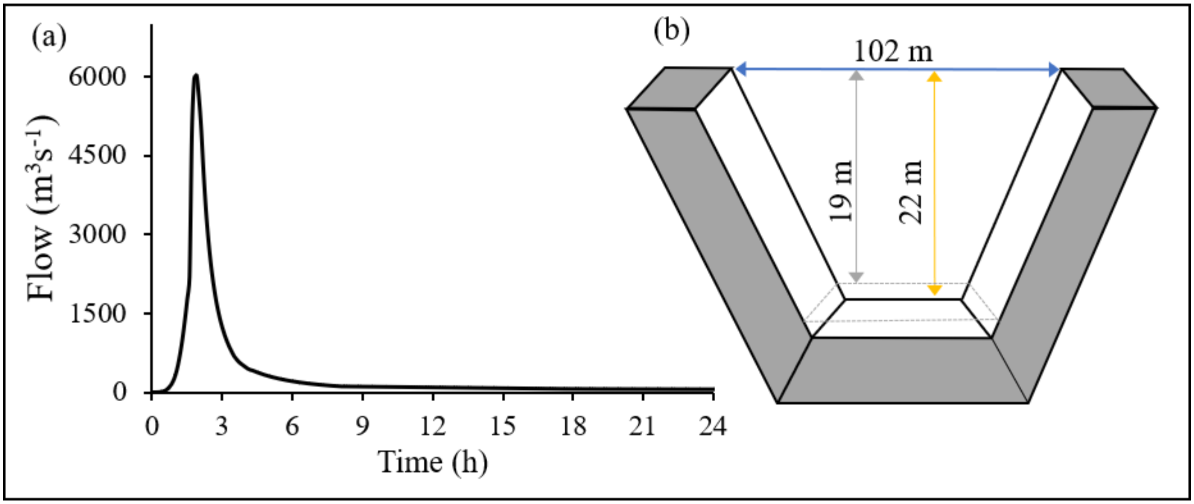

Figure 7. (a) A breach outflow hydrograph from the BREACH model; and (b) an illustration of breach parameters, breach width (↔), breach depth (↕), and the change in water surface elevation (↕).

4.1.2. Peak flow and flood travel time

Flow hydrographs at various locations along the flow path are provided in Figure 8. Conforming to the findings of Meyer et al. (2006), after approximately 6 hours, the GLOF had a peak discharge of 2,897 $m^3 s^{-1}$ as it reached Punakha Dzong, located 93 kilometres downstream of the lake. Peak flow at the WangdiRapid Station (shown in Figure 3(c)), 15 kilometres downstream of Punakha Dzong, was 2,455 $m^3 s^{-1}$, close to the recorded value of 2,539 $m^3 s^{-1}$. Here, the recorded flow rate included the contribution of normal flow from tributaries, which was not accounted for in our analysis. Good agreement of results for simulated flow and flood travel time with observed data, as well as previous studies, indicated that the performance of the employed models, and the modelling approach, were adequate and capable of yielding satisfactory results for predictive modelling of the target lake. Total inundated area along the basin was approximately 13.1 km^2.

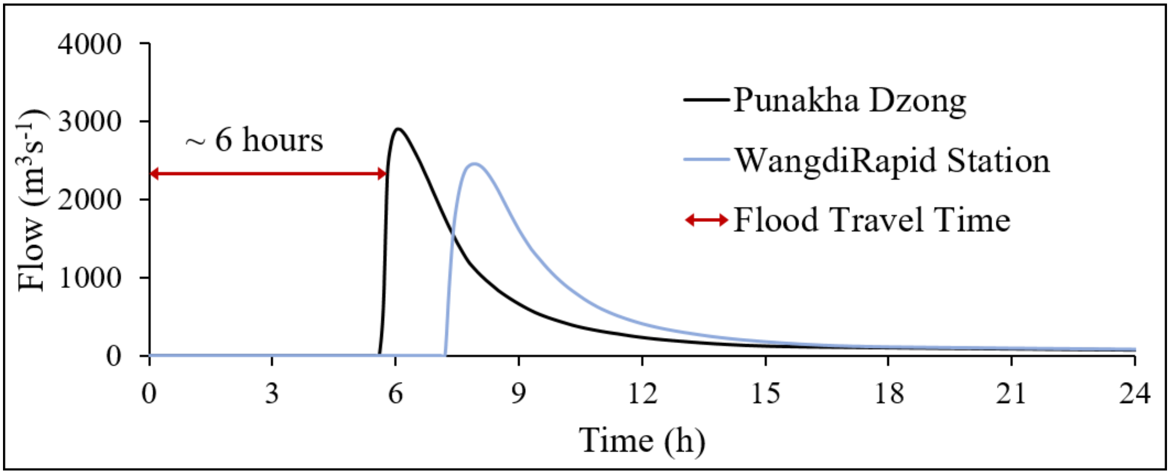

Figure 8. A simulated GLOF hydrograph at different locations along the flow path.

4.2. Future Thorthomi GLOF prediction

4.2.1. Lake bathymetry

Table 3 provides the estimated maximum depth and volume of the PDGLs using Equations (3) and (4), as proposed by Sakai (2012). The estimated volume and maximum depth of Thorthomi Lake based on Equations (3) and (4) were 400 million m^3 and 161 metres, respectively. The estimated volume and maximum depth of Thorthomi Lake falls within the predicted band, considering a 95% confidence level. The utilised equations showed a good relationship between area and volume, and area and maximum depth, with the prediction range of 281 million m^3 – 400 million m^3 – 560 million m^3 (lower bound – calculated value – upper bound) for volume prediction. The prediction range for maximum depth was between 130 meters – 161 meters – 270 meters. Compared to other glacial lakes in Bhutan, the estimated parameters from Table 3 indicate that the Thorthomi glacial lake is one of the largest and deepest lakes. The bathymetry of Thorthomi Lake, estimated based on the above parameters, is provided in Figure 9.

Table 3. List of potentially dangerous glacial lakes with measured lake volume and maximum depth, and estimated values using the relationship derived by Sakai (2012).

	Measured value (NCHM, 2019a)			Sakai (2012)	
Potentially dangerous glacial lakes (PDGL)	Area (km^2)	Volume (mil. m^3)	Max. Depth (m)	Volume (mil. M^3)	Max. Depth (m)

Mo_gl 202 (Latshokarp)	0.068	0.1	10	0.71	25.78
Mo_gl 234 (Sintaphu tsho)	0.238	6.4	54	4.81	47.44
Pho_gl 84	0.742	9.28	37.39	27.38	82.69
Pho_gl 148	0.637	26.3	101	21.68	76.75
Pho_gl 163 (Tarina I)	0.250	5.4	43	5.20	48.64
Pho_gl 164 (Tarina II)	0.446	13	67.5	12.56	64.48
Pho_gl 209 (Raphstreng)	1.242	54.6	110	60.20	106.36
Pho_gl 210 (Lugge Tsho)	1.46	65.19	96.93	77.11	115.11
Mang_gl 99 (GLT 9)	0.229	4.74	51.7	4.52	46.51
Mang_gl 106 (Metatshota)	1.2	41	120	57.12	104.58
Mang_gl 270 (Zanam F)	0.223	4.71	60.4	4.35	45.94
Mang_gl 307 (Zanam B)	0.862	37	103	34.43	88.971
Mang_gl 310 (Zanam G)	0.206	1.87	21.19	3.85	44.20
Cham_gl 198 (Phudung lake)	0.582	10.76	63	18.90	73.46
Cham_gl 383 (Chubda Tsho)	1.388	21.69	55.79	71.37	112.30
Thorthomi Lake	4.3	-	-	400	161

A recent study from Nepal proposed a glacial lake volume estimation equation by considering the width and length ratio of the lake (Qi et al., 2022). Based on the equation provided in Qi et al. (2022), the water volume of Thorthomi Lake can be estimated as 227 million m^3. This volume is substantially small compared to the volume estimated by Equation (4). The discrepancy may be related to the dataset used for each study, namely Equation (4) is based on lakes in Bhutan, Nepal, and Tibet; and Qi et al. (2022) is based on lakes in the Peruvian Andes and other areas, including non-morane-dammed lakes.

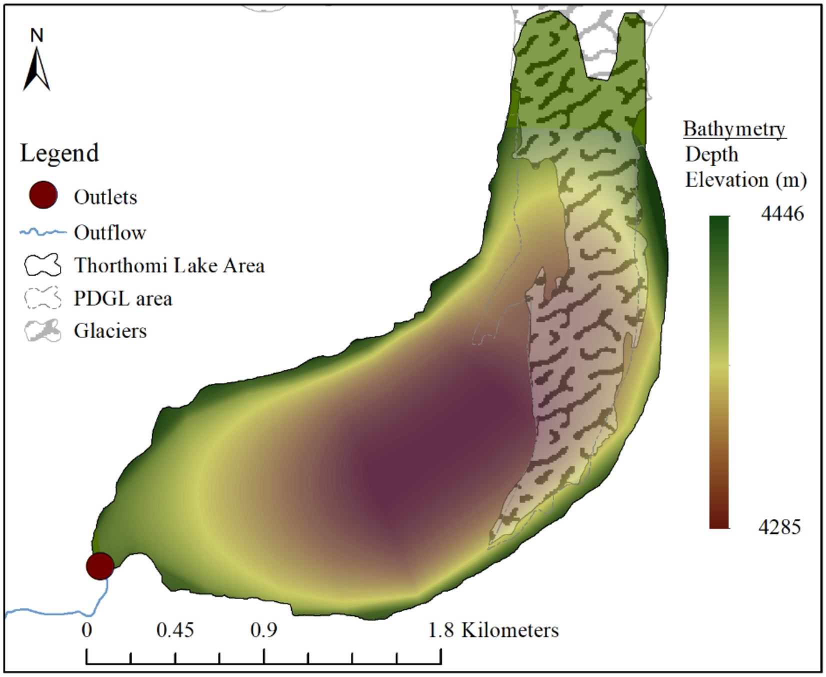

Figure 9. The estimated bathymetry of Thorthomi Lake.

4.2.2. Dam breach processes

Different dam breach scenarios for maximum breach, and a partial breach for a half breach width and depth (50% of maximum width and depth) were simulated to ascertain the potential risk under various breaching possibilities, including a partial dam breach, which occurred in 1994 (e.g., the 1994 Luggye GLOF). Simulated peak flow (*Qp*) resulting from the Thorthomi dam breach under different breach scenarios ranged from 9,700 $m^3 s^{-1}$ (for a 50% breach depth) to 16,360 $m^3 s^{-1}$ (for maximum breach width and depth), with, as shown in Figure 10 (a), a time to peak (*Tp*) of 3.4 to 4 hours, respectively. The bathymetry of the lake and the topography of the moraine dam dictates the total lake draw down depth and the volume of the outburst flood. In this study, we estimated that 100 metres of lake water depth will be lowered before the breach outflow channel becomes sufficiently stable, after sending 283 million m^3 (approximately 70% of estimated lake water) of flood water downstream (Figure 10 (b)). The breach outflow channel was assumed to be stable when its bottom elevation reached the natural bed level of the downstream channel and down-cutting ceased.

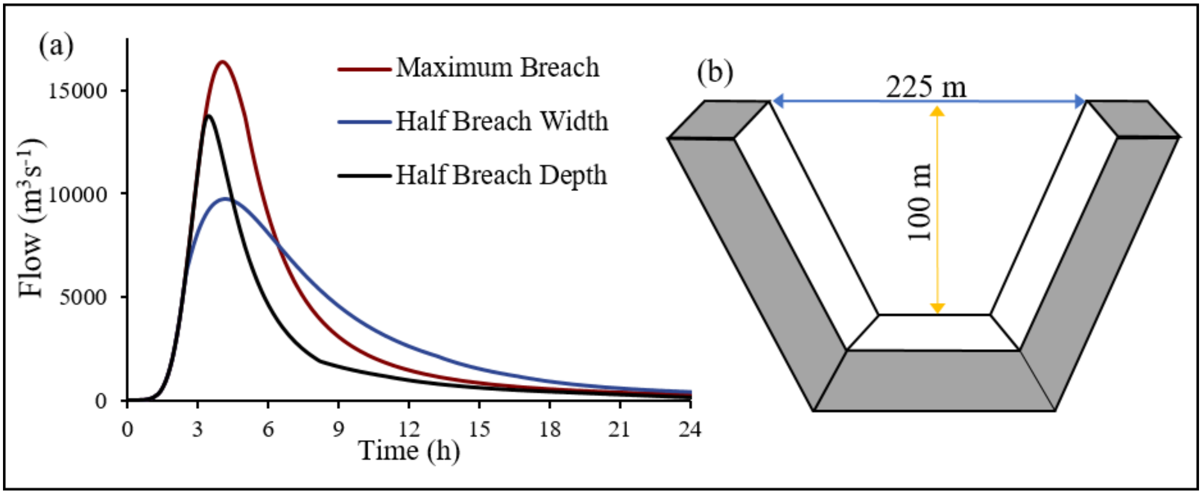

Figure 10. (a) A dam breach outflow hydrograph obtained from the BREACH model for three different scenarios; and (b) breach parameters, breach width (↔), and breach depth (↕) in metres for the maximum breach scenario.

4.3. Peak flow and flood travel time

The simulated flow hydrographs for three different scenarios at eight major settlement areas are provided in Figure 11. Peak flow of the GLOF gradually attenuated as it propagated downstream. Peak flow at Punakha Dzong ranged from 8,900 to 14,130 $m^3 s^{-1}$, and decreased from 8,200 to 11,500 $m^3 s^{-1}$ when it arrived at the hydropower plant (PHPA-I).

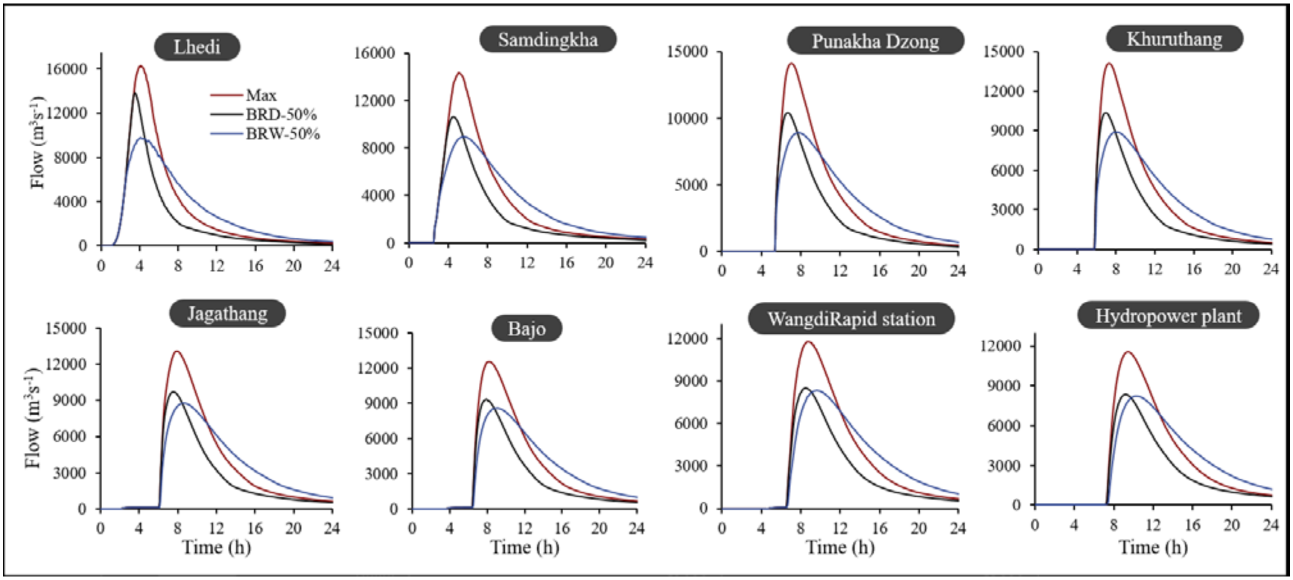

Figure 11. A simulated flow hydrograph at important locations, derived from the HEC-RAS result for each scenario. (Max: maximum breach, BRD-50%: half of maximum breach depth, BRW: half of maximum breach width).

Since such information is needed to estimate the area needed for evacuation and the lead time for evacuation, flood travel time and peak flow are essential parameters for early warning purposes. In this study, flood travel time was calculated based on timing of the breach outflow hydrograph and the flow hydrograph at the point of interest, when there was a significant inundation depth and extent. Peak flow is maximum simulated flow resulting from the dam breach, derived from the HEC-RAS simulation.

A schematic representation of an approximate distance, peak flow, averaged channel slope, and the estimated flood travel time for a maximum breach condition is provided in Figure 12. The estimated peak flow at Punakha Dzong, 14,130 $m^3 s^{-1}$, is expected to be over five times higher than the 1994 Luggye GLOF (the recorded value is 2,539 $m^3 s^{-1}$, and was estimated as 2,455 $m^3 s^{-1}$ in this study.)

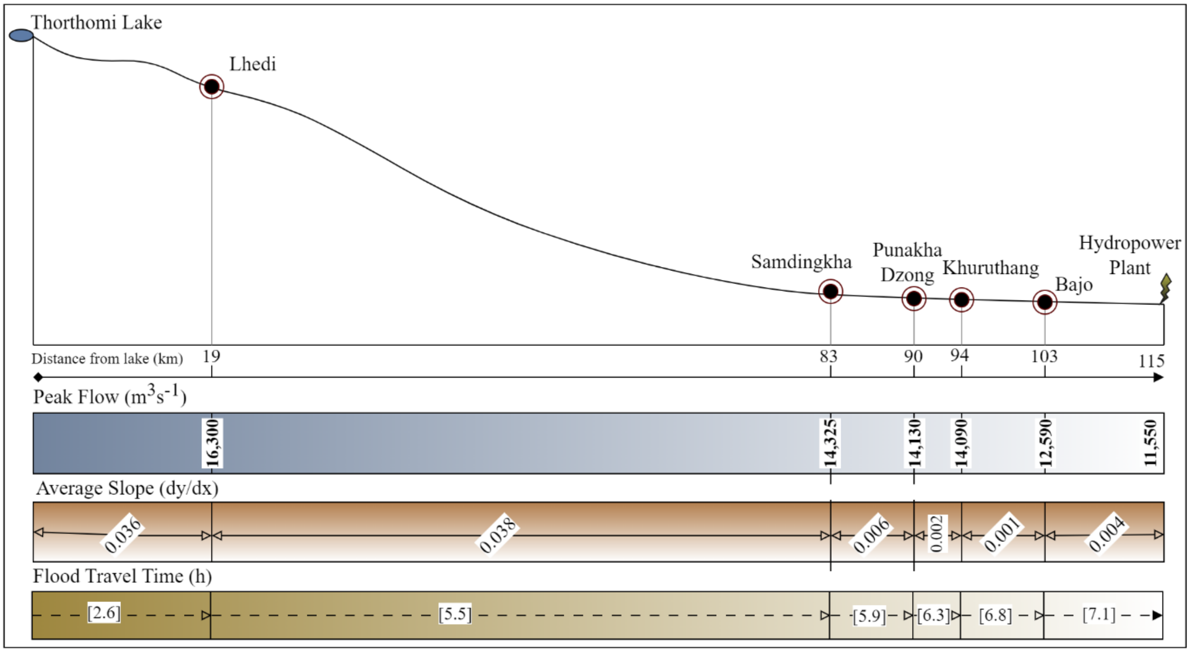

Figure 12. A schematic representation of flood parameters at six important locations along the flow path for the maximum breach scenario.

5. Discussions on future Thorthomi GLOF prediction

5.1. Inundation hazard in five vulnerable areas under the maximum breach scenario

The flood depth distribution, highlighting five vulnerable areas for a maximum breach scenario, is provided in Figure 13. The villages of Thanza, Toncho, and Lhedi, located in the northern-most part of the study area (see Figure 3), are expected to be inundated under a Thorthomi GLOF scenario. The 1994 Luggye GLOF also caused major damage to these settlement areas, but the severity of damage due to a Thorthomi GLOF is expected to be very high due to larger flood volume and shorter lead time. Major settlements along the river basin lie in the lower valleys of the Punakha and Wangdue districts, where large areas are expected to be flooded. Major towns and settlements, such as Samdingkha, Khuruthang, and Bajo, are expected to be inundated. The Mochhu River converges with the main river, the Phochhu River at the left-top of Figure 13(c). Substantial overflow surrounding the Mochhu River, around the confluence, has been predicted. This result is due to backwater flow from the Phochhu River. Water flow from the Mochhu River is not easy to estimate in advance and was accounted for in this study, so inundation surrounding Punakha Dzong may be underestimated. However, the contribution of water from the Mochhu River can be negligible because the base flow of the Mocchu River is approximately 100 m^3 s^{-1} and substantially small compared to estimated peak flow in this area, 14,130 m^3 s^{-1}. Total inundated area due to a Thorthomi GLOF, with a maximum breach, was estimated to be approximately 22 km^2, which is almost twice the area inundated under the Luggye GLOF simulation (13.1 km^2, estimated in this study).

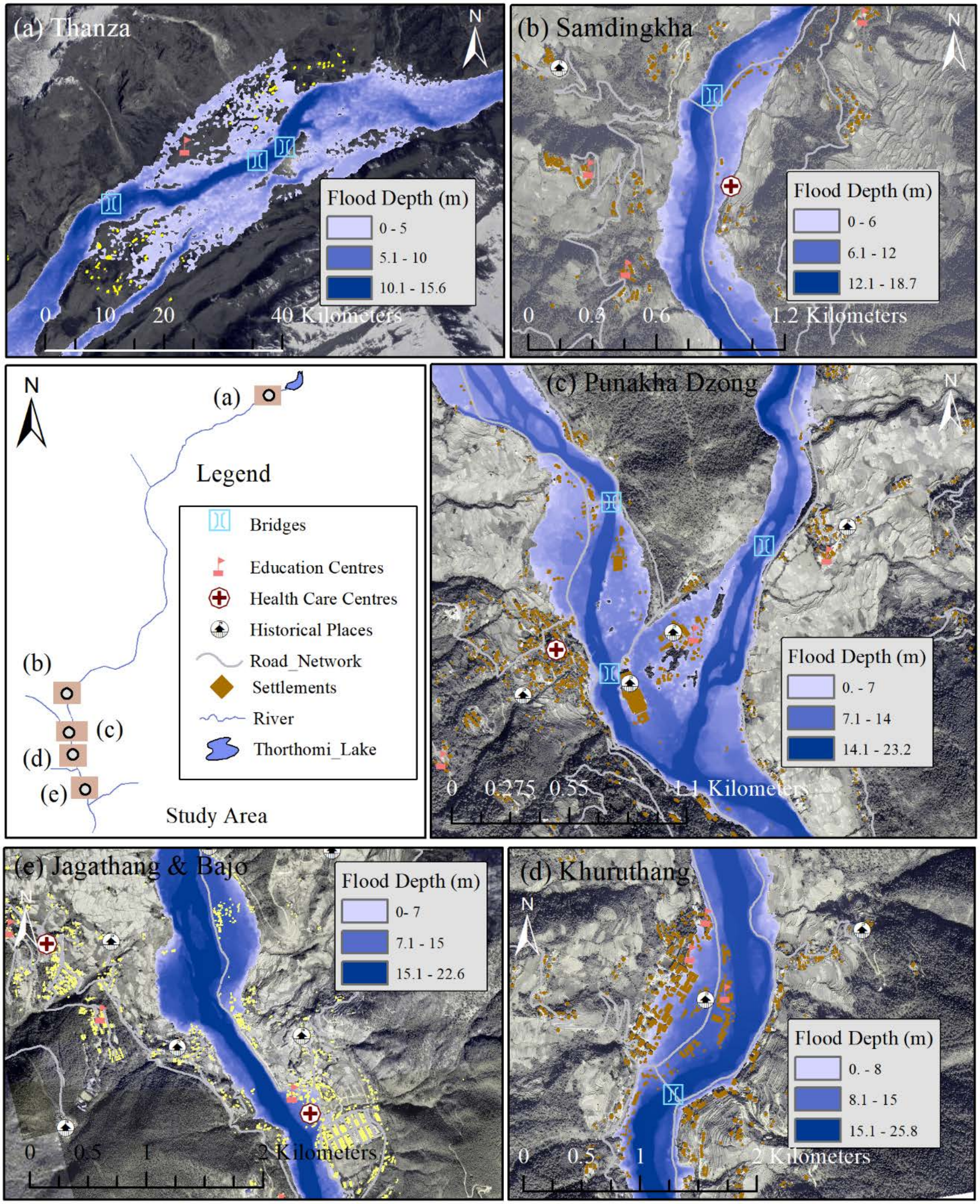

Figure 13. A maximum GLOF inundation map of the study area under the maximum breach scenario. Map data: Google Earth © 2023 CNES/Airbus, Maxar Technologies.

5.2. A comparison between three scenarios

Figure 14 compares the maximum inundation depth and extent for three different scenarios for the town of Khuruthang. Simulation results for the three scenarios considered in this study revealed that the overall inundation extent and flood depths were higher for the maximum breach scenario. However, the depth and flood extent for the two other scenarios were comparable to the maximum breach scenario. The results indicate that even for a partial breach of moraine dam, substantial damage within the downstream is expected. The results imply that the difference in glacial lake bathymetry may also affect the maximum inundation in downstream areas but is not very sensitive because of the nature of the GLOF event (consisting of a rapid dam breach process and flood routing in steep valleys.)

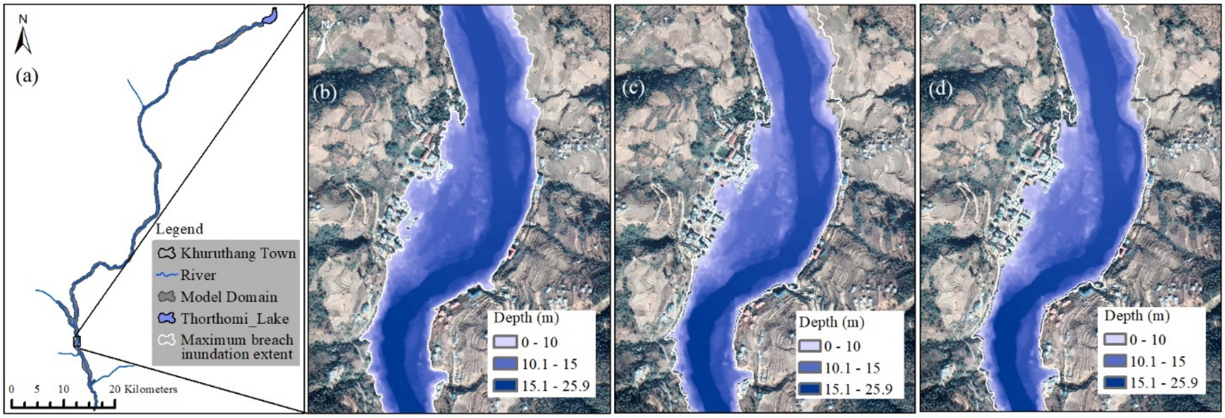

Figure 14. A comparison of inundation depth and extent for three breach scenarios within the Khuruthang study area. (a) A model domain highlighting Khuruthang Town. (b) The maximum breach scenario. (c) A 50% breach depth scenario. (d) A 50% breach width scenario. Map data: Google Earth © 2023 CNES/Airbus, Maxar Technologies.

5.3. Time series change of flood depth distribution surrounding Punakha Dzong

The spatial distribution of flood depth for a maximum breach scenario, at different time steps, for Punakha Dzong and Khuruthang town are provided in Figure 15. Due to higher peak flow and a longer flood duration, overall flood hazard potential for the inhabited area of the Thorthomi Lake GLOF, as compared to the 1994 Luggye GLOF, was significantly higher. Most of the flood path lies in the narrow V-shaped valley, where there are few to no settlements or infrastructure. We estimated that over 1,277 houses, most in the lower region of the study area, will be inundated in a GLOF. Aside from this, infrastructures such as roads, bridges, and sand dredging equipment will be damaged.

Notable damage during the 1994 GLOF occurred in Punakha Dzong. The area near the dzong was completely inundated in the 1994 Luggye GLOF. As shown in Figures 13 and 15, the simulated future GLOF indicates that the Punakha Dzong area will be completely flooded, with a maximum depth of over 10 metres.

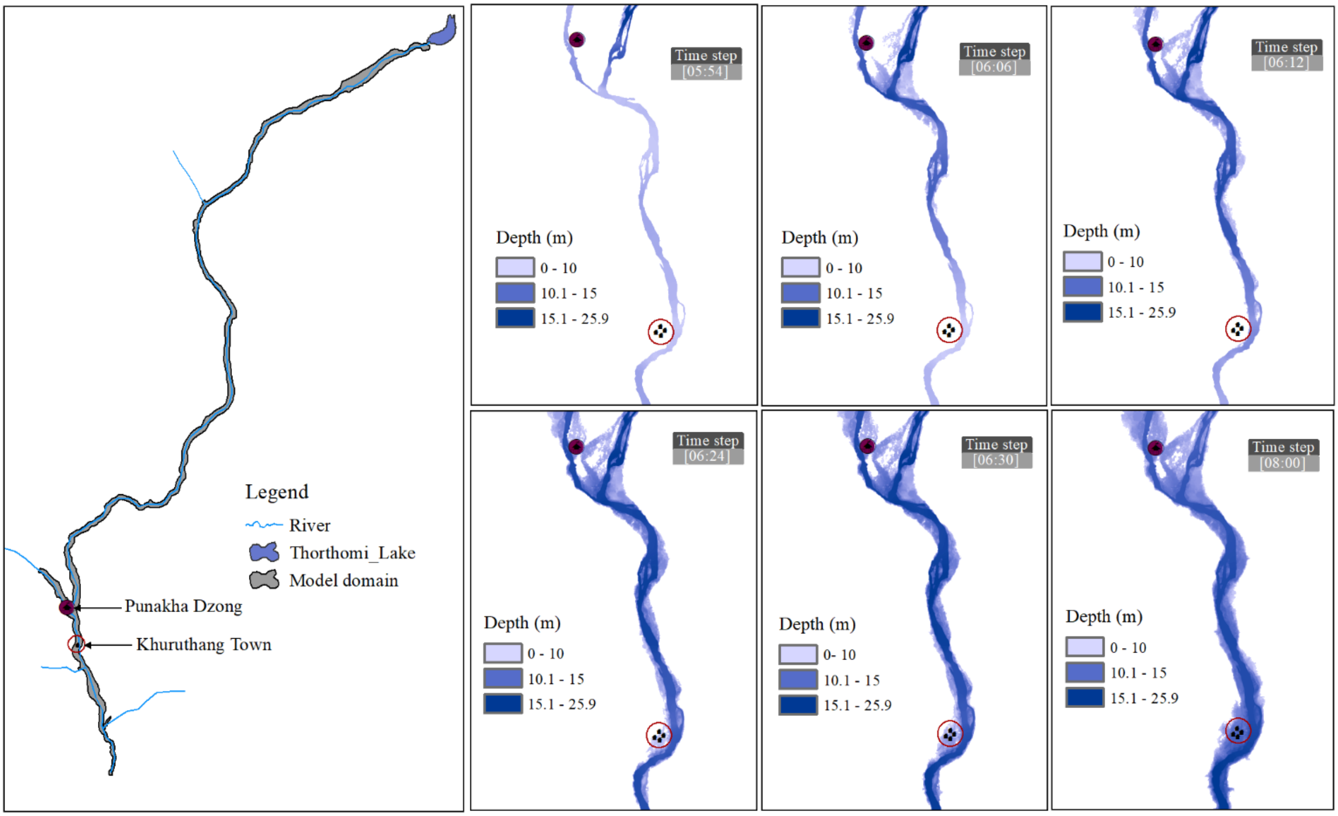

Figure 15. The temporal change of the spatial extent of flood depth at Punakha Dzong and Khuruthang. (a) The hydrodynamic model domain. (b - g) The inundation depth at six time steps.

5.4. Socio-economic impact

The Punakha (the middle-downstream of the domain, see Figure 13) and the Wangdue districts (consisting of the Bajo and Jagathang settlements, and the downstream domain, see Figures 3 and 13) are leading producers of rice, an essential crop for the country’s GDP and food security. Any damage to agricultural land would have a devastating impact on farmers and the nation. Aside from potential damage to buildings and infrastructure, such as roads and bridges, agricultural land would also become submerged and destroyed by a flood. We estimated that approximately 193 to 245 hectares of agricultural land will be inundated under different scenarios in a Thorthomi GLOF event. Figure 16 shows the potential extent of floods for different land use classes and highlights probable damage to agricultural land, particularly in the areas of Samdingkha and Jagathang. The overall hazard potential of a GLOF from Thorthomi Lake under different scenarios is summarised in Table 4. Although the peak flow rate of each scenario is different (29% to 37% between the maximum and minimum for the result depicted in Figure 11), the total inundation area, the number of submerged buildings, and the area of impacted cultivated land are not much different (12%, 22%, and 21%, respectively), implying that the estimated flood is significant even for the most minor flood scenario (BRW-50% scenario) for the Thorthomi GLOF. The scenarios indicate that most of the damage will occur for river properties and that farmland will be substantially damaged, even when a dam breach is not drastic. The soil in farmlands will also be eroded and covered by debris. Damage to irrigation is expected and may affect agriculture in farmland located behind flooded areas. Over the long-term, damage to soil and irrigation would extensively reduce farmers' production. In advance, careful evacuation planning and business continuity planning (e.g., JICA, 2015), including a plan for agriculture, are essential for mitigating damage caused by a future Thorthomi GLOF.

Table 4. The damage potential of a GLOF from Thorthomi Lake.

Hazards→ Scenarios↓	Total inundation area (km^2)	Number of buildings inundated	Total cultivated agricultural land impacted (ha)
Maximum breach	22.7	1277	245.6
½ breach depth	20.8	1044	206.4
½ breach width	19.9	1000	193.4

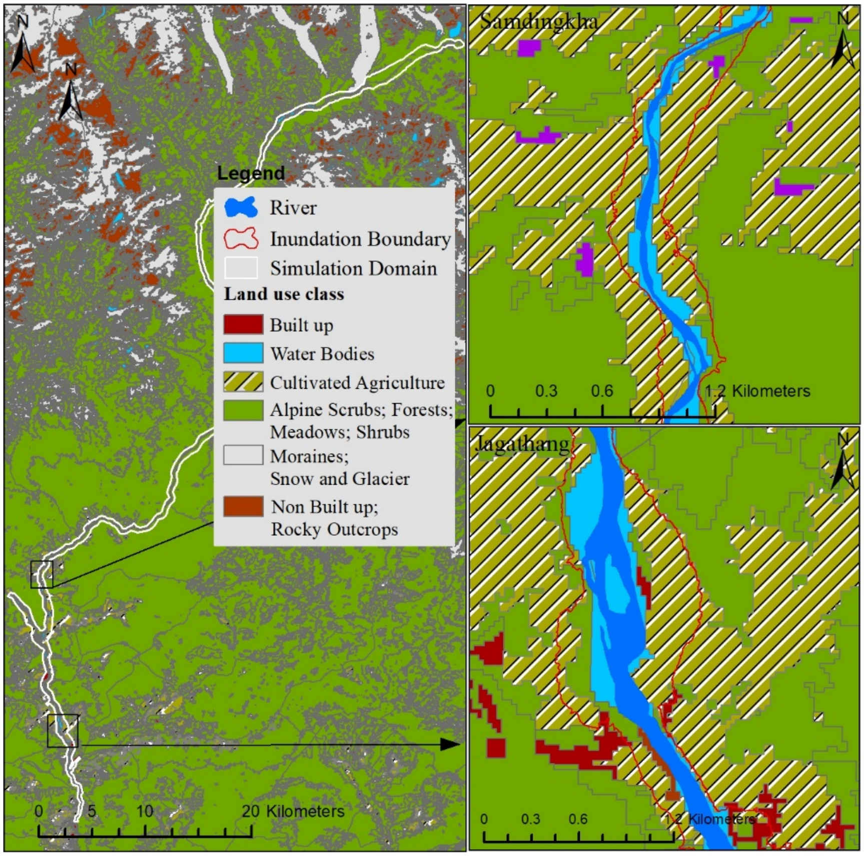

Figure 16. The probable GLOF inundation extent on land use classes. (Land use data source: National Land Commission Secretariat, Bhutan).

5.5. Limitations of this study

Since, due to a lack of actual surveyed data, volume and maximum depth were estimated based on the statistical relationships established by past studies, the estimated bathymetry of Thorthomi Lake is a major limitation of our study. As compared to the bathymetry presented, the use of actual, surveyed bathymetric data may yield a more accurate prediction. An additional limitation of our study is the clear water assumption. Compared to clear water, hyper-concentrated water has different dynamic properties. Debris in flood water may cause substantial damage to farmland, infrastructure, and human life. Research on glacial lakes and their outburst floods is an emerging field (e.g., Qi et al., 2022; Taylor et al., 2023). To obtain more accurate damage predictions, data and methods should be revised following research progress.

6. Conclusion

We explored future hazards and damages arising from a GLOF from Thorthomi Lake, one of the potentially dangerous glacial lakes in Bhutan but not well investigated within a scientific literature to date. To validate the approach used in this study and to calibrate the model, and prior to assessing the hazards of a Thorthomi GLOF, we reconstructed the 1994 Luggye Lake GLOF. The BREACH model was used to estimate the outflow hydrograph emanating from a failure of moraine dams due to overtopping flow. Moraine materials and soil parameters used to parameterise the model were obtained from a report published by the National Center for Hydrology and Meteorology (NCHM), Bhutan. Propagation of the GLOF was simulated using a 2D routing module in HEC-RAS for modelling unsteady flow, which is an inherent characteristic of a GLOF where there is a sharp rise in the flow hydrograph.

The bathymetry of Thorthomi Lake was estimated based on a regression equation derived from the relationship between lake area-depth-volume found within moraine lakes. We estimated that the total volume of the lake is approximately 400 million m^3, with a maximum depth of 161 metres. According to the maximum breach scenario, the Thorthomi GLOF may release 283 million m^3 of water in under 12 hours, with a peak flow rate of 16,360 m^3/s, occurring approximately 4 hours following initiation of the breaching process. Outflow hydrographs estimated by the model were used as input for the upstream boundary condition in hydrodynamic modelling.

Flood routing was performed to reach a length of approximately 115 km, and then peak discharge, the flood travel time, and flood depths at locations where settlements exist were estimated. According to the maximum breach scenario, Punakha Dzong, which lies 90 km downstream of Thorthomi Lake and at the beginning of major settlements, would witness a peak discharge of 14,128 m^3/s, approximately six hours following breach initiation. A potential GLOF from Thorthomi Lake would cause extensive agricultural and infrastructural damage to 245 hectares of agricultural lands, and, for a maximum breach scenario, 1,277 buildings are expected to be inundated. Comparable damage is also expected for two minor flood scenarios, implying that such damage is inevitable for a future Thorthomi GLOF.

The close proximity of glacial lakes within the Lunana region, especially the Thorthomi and Rapstreng Lakes (see Figure 4) pose an even greater potential risk due to a possible cascading GLOF event. Failure of the lateral moraine of Thorthomi Lake would lead to lake water breaching into Rapstreng Lake, which would consequently cause the failure of its moraine dam. To better understand the potential risk of cascading events, such possibilities should also be explored. Since our study considered failure of the terminal moraine in the direction of the existing outlet, it is highly unlikely for such an event to occur under the current scenario. Accordingly, a cascading GLOF was not assessed in our study.

The hazard assessment of GLOF plays a crucial role for understanding and mitigating the risks associated with these devastating natural events. Our study quantified the large potential a Thorthomi GLOF will pose to downstream settlements and infrastructure. Such assessments will enable policymakers, local communities, and relevant stakeholders to make informed decisions regarding land use planning, disaster preparedness, and early warning systems.

Since glacial environments are dynamic and subject to change due to climate variations, GLOF hazard assessments are not static. Continuous monitoring and regular reassessments of glacial lakes and associated hazards are essential to account for environmental shifts and to ensure the effectiveness of mitigation strategies. Furthermore, a multi-disciplinary approach in GLOF hazard assessments is necessary. Collaborations between researchers, policymakers, local communities, and other stakeholders are essential for effective decision-making, disaster preparedness, and the implementation of mitigation measures. To essentially reduce GLOF risk, the development of methods to safely release dammed water to downstream areas is important.

Data availability

Our study used open and commercial data. Commercial data may be distributed by following license terms and conditions.

Author contributions

TW: conceptualization, data curation, method, writing original draft
RT: conceptualization, data curation, draft writing, reviewing and editing

Competing interests

The authors declare no conflict of interest.

Acknowledgments

TW acknowledges a Human Resource Development scholarship from the Japan International Cooperation Agency (JICA). We acknowledge Professors Yuji Toda and Takashi Tashiro, and other lab members of the Hydraulic Research Laboratory at Nagoya Univesity. We also express our gratitude to Dr. Shigeo Suizu, Dr. Tomoyuki Wada, and Mr. Toru Koike at Earth System Science Co., Ltd. We sincerely thank members of the National Center for Hydrology and Meteorology for their continued support of our study.

References

Awal, R., Nakagawa, H., Fujita, M., Kawakie, K., Baba, Y., and Zhang, H.: Experimental study on glacial lake outburst floods due to waves overtopping and erosion of moraine dam.Annuals of Disas. Prev. Res. Inst. Kyot Univ. No. 53(B), 583–594. 2010.

Bajracharya, B., Shrestha, A. B., and Rajbhandari, L.: Glacial lake outburst floods in the Sagarmatha region: Hazard assessment using GIS and hydrodynamic modelling, Mountain Research and Development, 27(4), 336–344, https://doi.org/10.1659/mrd.0783, 2007.

Begam, S., Sen, D., and Dey, S.: Moraine dam breach and glacial lake outburst flood generation by physical and numerical models. Journal of Hydrology, 563, 694–710, https://doi.org/10.1016/j.jhydrol.2018.06.038, 2018.

Brunner, G. W.: HEC-RAS River Analysis System Hydraulic Reference Manual, In Hydrologic Engineering Center (Issue February), 2016.

Brunner, G. W., and CEIWR-HEC.: HEC-RAS River Analysis System: User Manual 1D and 2D Version 5.0. US Army Corps of Engineers, February, 1–790, 2016.

Casas, A., Benito, G., Thorndycraft, V. R., and Rico, M.: The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling, Earth Surface Processes and Landforms, 31(4), 444–456, https://doi.org/10.1002/esp.1278, 2006.

Clague, J. J., and Evans, S. G.: A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews A review of catastrophic drainage of moraine-dammed lakes in British Columbia, Quaternary Science Reviews, 19, 1763–1783, 2000.

Cook, S. J., and Quincey, D. J.: Estimating the volume of Alpine glacial lakes. Earth Surface Dynamics, 3(4), 559–575, https://doi.org/10.5194/esurf-3-559-2015, 2015.

Fread, D. L.: BREACH: An Erosion Model for Earthen Dam Failure, Hydrologic Research Laboratory, National Weather Service, National Oceanic and Atmospheric Administration,1988.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T., and Yamanokuchi, T.: Potential flood volume of Himalayan glacial lakes, Natural Hazards and Earth System Sciences, 13(7), 1827–1839, https://doi.org/10.5194/nhess-13-1827-2013, 2013

Fujita, Koji, Suzuki, R., Nuimura, T., and Sakai, A.: Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya, Journal of Glaciology, 54(185), 220–228, https://doi.org/10.3189/002214308784886162, 2008.

Gardelle, J., Arnaud, Y., and Berthier, E.: Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009, Global and Planetary Change, 75(1–2), 47–55, https://doi.org/10.1016/j.gloplacha.2010.10.003, 2011.

Gurung, D. R., Khanal, N. R., Bajracharya, S. R., Tsering, K., Joshi, S., Tshering, P., Chhetri, L. K., Lotay, Y., and Penjor, T.: Lemthang Tsho glacial Lake outburst flood (GLOF) in Bhutan: cause and impact, Geoenvironmental Disasters, 4(1), https://doi.org/10.1186/s40677-017-0080-2, 2017.

Gyasi-Agyei, Y., Willgoose, G., and De Troch, F. P.: Effects of vertical resolution and map scale of digital elevation models on geomorphological parameters used in hydrology, Hydrological Processes, 9(3–4), 363–382, https://doi.org/10.1002/hyp.3360090310, 1995.

Hagg, W., Ram, S., Klaus, A., Aschauer, S., Babernits, S., Brand, D., Guggemoos, P., and Pappas, T.: Hazard assessment for a glacier lake outburst flood in the mo chu river basin, Bhutan, Applied Sciences (Switzerland), 11(20), https://doi.org/10.3390/app11209463, 2021.

Hawker, L., Uhe, P., Paulo, L., Sosa, J., Savage, J., Sampson, C., and Neal, J.: A 30 m global map of elevation with forests and buildings removed, Environmental Research Letters, 17(2), https://doi.org/10.1088/1748-9326/ac4d4f, 2022.

Heathcote, A. J., Giorgio, P. A., and Prairie, Y. T.: Predicting bathymetric features of lakes from the topography of their surrounding landscape, Canadian Journal of Fisheries and Aquatic Sciences, 72(5), 643–650, https://doi.org/10.1139/cjfas-2014-0392, 2015.

Horritt, M. S., and Bates, P. D.: Effects of spatial resolution on a raster based model of flood flow, Journal of Hydrology, 253(1–4), 239–249, https://doi.org/10.1016/S0022-1694(01)00490-5, 2001.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., and Paul, F.: Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps, Canadian Geotechnical Journal, 39(2), 316–330, https://doi.org/10.1139/t01-099, 2002.

Japan International Cooperation Agency.: Feasibility study on the Development of Punatsang Chhu Hydropower Project in the Kingdom of Bhutan, Final Report, 2001.

Japan International Cooperation Agency.: Natural Disaster Risk Assessment and Area Business Continuity Plan Formulation for Industrial Agglomerated Areas in the ASEAN Region Risk Profile Report – Hai Phong of Vietnam, 2015.

Karma.: Reducing Lake Water Level in Thorthormi Glacial Lake in Bhutan : An Adaptation Project to the Adverse Impact of Climate Change, 2013.

Koike, T., and Takenaka, S.: Scenario Analysis on Risks of Glacial Lake Outburst Floods on the Mangde Chhu River, Bhutan, Global Environmental Research, 16, 41–49, 2012.

Komori, J., Koike, T., Yamanokuchi, T., and Tshering, P.: Glacial Lake Outburst Events in the Bhutan Himalayas, Global Environmental Research, 16(February 2012), 59–70, 2012.

Leber, D., Haeuser, H., Brauner, M., and Skuk, S.: Luggye Tsho Outburst Flood Mitigation Project, Lunana, Bhutan, Technical Report, 2000.

Maskey, S., Kayastha, R. R. B., and Kayastha, R. R. B.: Glacial Lakes Outburst Floods (GLOFs) modelling of Thulagi and Lower Barun Glacial Lakes of Nepalese Himalaya, Progress in Disaster Science, 7, 100106, https://doi.org/10.1016/j.pdisas.2020.100106, 2020.

Meyer, M. C., Wiesmayr, G., Brauner, M., Häusler, H., and Wangda, D.: Active tectonics in Eastern Lunana (NW Bhutan): Implications for the seismic and glacial hazard potential of the Bhutan Himalaya, Tectonics, 25(3), https://doi.org/10.1029/2005TC001858, 2006.

Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Gurung, D. R., and Joshi, S. P.: Inventory of Glaciers, Glacial Lakes and GLOF, 53(9), 1689–1699, 2001.

Mosquera-Machado, S., and Ahmad, S.: Flood hazard assessment of Atrato River in Colombia, Water Resources Management, 21(3), 591–609, https://doi.org/10.1007/s11269-006-9032-4, 2007.

National Center for Hydrology and Meteorology.: Bhutan Glacial Lake Inventory (BGLI) 2021, Cryosphere Services Division, Bhutan, 2021.

National Center for Hydrology and Meteorology.: Detailed Assessment Report on GLOF Hazard from Thorthomi Glacial Lake and Associated Glaciers, 2019a.

National Center for Hydrology and Meteorology.: Reassessment of Potentially Dangerous Glacial Lakes in Bhutan, Cryosphere Services Division, Bhutan, 2019b.

Neupane, R., Chen, H., and Cao, C.: Review of moraine dam failure mechanism, Geomatics, Natural Hazards and Risk, 10(1), 1948–1966, https://doi.org/10.1080/19475705.2019.1652210, 2019.

National Statistics Bureau.: Agriculture Survey Report 2021, 2021.

National Statistics Bureau.: 2017 Population and housing census of Bhutan, national report, 2018

O'Connor, J. E., Hardison, J. H., and Costa, J. E.: Debris flows from failures of neoglacial-age moraine dams in the Three Sisters and Mount Jefferson wilderness areas, Oregon, In US Geological Survey Professional Paper (Issue 1606), 2001.

Porter, S. A., Tomer, M. D., James, D. E., and Boomer, K. M. B.: Agricultural Conservation Planning Framework ArcGIS Toolbox User's Manual Version 2.2 (p. 82), http://northcentralwater.org/acpf/, 2016.

Qi, M., Liu, S., Wu, K., Zhu, Y., Xie, F., Jin, H., Gao, Y., and Yao, X.: Improving the accuracy of glacial lake volume estimation: A case study in the Poiqu basin, central Himalayas. Journal of Hydrology, 610, p.127973, https://doi.org/10.1016/j.jhydrol.2022.127973, 2022.

Richardson, S. D., and Reynolds, J. M.: An overview of glacial hazards in the Himalayas, Quaternary International, 65–66, 31–47, https://doi.org/10.1016/S1040-6182(99)00035-X, 2000.

Rinzin, S., Zhang, G., Sattar, A., Wangchuk, S., Allen, S. K., Dunning, S., and Peng, M.: GLOF hazard, exposure, vulnerability, and risk assessment of potentially dangerous glacial lakes in the Bhutan Himalaya, Journal of Hydrology, 619 (October 2022), 129311, https://doi.org/10.1016/j.jhydrol.2023.129311, 2023.

Sakai, A.: Glacial Lakes in the Himalayas : A Review on Formation and Expansion Processes, Global Environmental Research, 16(2011), 23–30, 2012.

Sattar, A., Haritashya, U. K., Kargel, J. S., Leonard, G. J., Shugar, D. H., and Chase, D. V.: Modeling lake outburst and downstream hazard assessment of the Lower Barun Glacial Lake, Nepal Himalaya, Journal of Hydrology, 598, 126208, https://doi.org/10.1016/j.jhydrol.2021.126208, 2021.

Shahrim, M. F., and Ros, F. C.: Estimation of breach outflow hydrograph using selected regression breach equations, IOP Conference Series: Earth and Environmental Science, 476(1), https://doi.org/10.1088/1755-1315/476/1/012129, 2023.

Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J., and Westoby, M.: Glacial lake outburst floods threaten millions globally, Nature Communications, 14(1), 487, https://doi.org/10.1038/s41467-023-36033-x, 2023.

Tsubaki, R., and Kawahara, Y.: The uncertainty of local flow parameters during inundation flow over complex topographies with elevation errors, Journal of Hydrology, 486, 71–87, https://doi.org/10.1016/j.jhydrol.2013.01.042, 2013.

United Nations International Strategy for Disaster Reduction.: The Human Cost of Weather Related Disaster, Centre for

Research on the Epidemiology of Disasters, 1-30, 2015.

Vuichard, D., and Zimmermann, M.: The 1985 Catastrophic Drainage of a Moraine-Dammed Lake , Khumbu Himal , Nepal : Cause and Consequences, International Mountain Society, Mountain Research and Development, 7(2), 91–110, https://www.jstor.org/stable/3673305, 1987.

Wang, X., Liu, S., Guo, W., and Xu, J.: Assessment and simulation of glacier lake outburst floods for longbasaba and Pida lakes, China, Mountain Research and Development, 28(3–4), 310–317, https://doi.org/10.1659/mrd.0894, 2008.

Watanabe, T., and Rothacher, D.: The 1994 Lugge Tsho Glacial Lake Outburst Flood, Bhutan Himalaya, Mountain Research and Development, 16(1), 77, https://doi.org/10.2307/3673897, 1996.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., Reynolds, J. M., Hassan, M. A. A. M., and Lowe, A.: Numerical modelling of glacial lake outburst floods using physically based dam-breach models, Earth Surface Dynamics, 3(1), 171–199, https://doi.org/10.5194/esurf-3-171-2015, 2015.

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J., and Reynolds, J. M.: Modelling outburst floods from moraine-dammed glacial lakes, Earth-Science Reviews, 134, 137–159, https://doi.org/10.1016/j.earscirev.2014.03.009, 2014.

Worni, R., Huggel, C., Clague, J. J., Schaub, Y., and Stoffel, M.: Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective, Geomorphology, 224, 161–176, https://doi.org/10.1016/j.geomorph.2014.06.031, 2004.

Xu, K., Fang, J., Fang, Y., Sun, Q., Wu, C., and Liu, M.: The Importance of Digital Elevation Model Selection in Flood Simulation and a Proposed Method to Reduce DEM Errors: A Case Study in Shanghai, International Journal of Disaster Risk Science, 12(6), 890–902, https://doi.org/10.1007/s13753-021-00377-z, 2021.

Yamada, T., Naito, N., Koshima, S., Fushimi, H., Nakazawa, F., Segawa, T., Uetake, J., Suzuki, R., Sato, N., Karma, Chhetri, I. K., Gyenden, L., Yabuki, H., and Chikita, K.: Outline of 2002-research activities on glacier lakes in Lunana region, Bhutan Himalayas, Bulletin of Glaciological Research, 21, 79–90, 2004.

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P. D., Allen, G. H., and Pavelsky, T. M.: MERIT Hydro: A High-Resolution Global Hydrography Map Based on Latest Topography Dataset, Water Resources Research, 55(6), 5053–5073, https://doi.org/10.1029/2019WR024873, 2019.

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O’Loughlin, F., Neal, J. C., Sampson, C. C., Kanae, S., and Bates, P. D.: A high-accuracy map of global terrain elevations, Geophysical Research Letters, 44(11), 5844–5853, https://doi.org/10.1002/2017GL072874, 2017.

Yamazaki, D., Sato, T., Kanae, S., Hirabayashi, Y., and D.Bates, P.: Regional flood dynamics in a bifurcating mega delta simulated in a global river model, Geophysical Research Letters, 41(April), 3127–3135, https://doi.org/10.1002/2014GL059744, 2014.

Ye, A., Zhou, Z., You, J., Ma, F., and Duan, Q.: Dynamic Manning’s roughness coefficients for hydrological modelling in basins, Hydrology Research, 49(5), 1379–1395, https://doi.org/10.2166/nh.2018.175, 2018.

Zhu, S., Liu, B., Wan, W., Xie, H., Fang, Y., Chen, X., Li, H., Fang, W., Zhang, G., Tao, M., and Hong, Y.: A new digital lake bathymetry model using the step-wise water recession method to generate 3D lake bathymetric maps based on DEMs, Water (Switzerland), 11(6), https://doi.org/10.3390/w11061151, 2019.