Anticipating Glacier Lake Outburst Floods (GLOFs): an impact-based forecasting framework for managing GLOF risks in Nepal.

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Grace Elizabeth Muir - MSc Thesis

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Abstract

This study explores the emerging topics of anticipatory action and impact-based forecasting within the context of glacier lake outburst floods (GLOFs) in mountainous Nepal. The overall purpose of the research is to assess how the development of impact-based forecasts could guide humanitarian preparedness activities in Nepalese communities exposed to GLOF risks. By synthesizing the state of existing risk knowledge on potentially dangerous glacier lakes, and assessing how forecast-based actions are applied to other hazard types, the following research questions are addressed:

1. *How are glacier lake outburst flood risks to Nepalese communities presented in academic literature?*
2. *How could impact-based forecasting address glacier lake outburst flood risks in Nepal?*

A systematic literature review was undertaken to collate insights from academic studies for the first research question, with significant data gaps and discrepancies identified within and across existing risk models. To address the second research question, interviews were conducted with actors working with anticipatory action and impact-based forecasting. These insights were then correlated with the evolving understanding of the GLOF risk landscape in Nepal to propose an impact-based forecasting framework for managing GLOF threats. The framework presented demands advanced investment in understanding and monitoring GLOF triggers, a noted prerequisite for enhancing prediction and forecasting capacities, making this a key area for future research.

Keywords

Anticipatory Action, Impact-based Forecasting, Glacier Lake Outburst Flood, Nepal, Risk-informed Early Action, Prediction, Disaster Risk Management

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Summary

Glacier lake outburst floods (GLOFs) are an increasingly documented threat across the Himalayan region, wherein Nepal is situated. GLOFs involve a rapid discharge of water from a lake situated at the side, front, within, beneath, or on the surface of a glacier. Forecasting the impacts associated with such events could facilitate the development of proactive risk management approaches. Impact-based forecasting (IbF) and anticipatory action (AA) are proactive strategies which are of emerging interest among humanitarian actors and disaster risk management authorities both in Nepal and globally.

To assess what a proactive approach could look like for addressing GLOF risks in Nepal, this thesis takes inspiration from existing GLOF risk models and applications of anticipatory risk management approaches for other hazard types. The research questions addressed are as follows:

1. *How are glacier lake outburst flood risks to Nepalese communities presented in academic literature?*
2. *How could impact-based forecasting address glacier lake outburst flood risks in Nepal?*

A systematic literature review of potentially dangerous glacier lake (PDGL) risk models enabled the assessment of existing capacities to anticipate GLOF threats. The research also collates insights from experiences in applications of IbF through six semi-structured interviews and a non-systematic content analysis of IbF and AA documents. Both research components ultimately inform a framework showing how GLOF risks could be addressed through IbF.

Part 1 of the thesis looks at the state of risk data for GLOFs in Nepal, presenting an overview of PDGLs and associated outburst models. The findings show that of the 47 classified PDGLs posing a risk to Nepal, only four are assessed to have outburst models quantifying projected impacts using physically-based hydrodynamic models. Although, there is high uncertainty and discrepancies in projected inundation zones and lead times across studies for all assessed lakes. Most studies additionally do not assess household-level vulnerabilities, serving as a key knowledge gap in capacities to anticipate impacts in a way that is meaningful for holistically risk-informed activities.

Part 2 discusses the results of the study around the proposed framework, showing how GLOF threats in Nepal could be addressed through IbF. First, capacities to predict GLOF events are discussed under two categories, the longer-term readiness triggers, and shorter-term activation triggers. The GLOF risk assessments studied model an array of trigger and outburst mechanisms that could theoretically be observed at each PDGL to assess the likelihood of imminent outburst and aligned with anticipated outburst scenarios. Some examples of assessed triggers include mass movements, high temperatures or precipitation, and earthquakes. A discussion of the lead times available for implementing risk-mitigating early actions upon recognition of these triggers follows this.

Next the two overarching phases of the framework, the readiness phase, and the activation phase, are expanded upon, discussing the proposed activities within each. The

readiness phase involves the long-term anticipation of GLOF-related impacts to enable the implementation of risk-informed preparedness activities. The overarching stages of this phase include identifying PDGLs, developing impact-based forecasts, and developing early action protocols. A related theme drawn from the interview respondents regards the importance of IbF-informed preparedness activities such as developing community capacities to operationalise forecasts and implement early actions. The activation phase is the period for refining IbF scenarios and implementing predefined early actions. An issue emerging from the interviews was that of working with dynamic risk data in anticipatory action. It is suggested this could be mitigated in the GLOF context by enabling scenarios and associated protocols to be refined according to emerging risk information.

This thesis ultimately provides an assessment of the risk data associated with GLOFs in Nepal and proposes an IbF framework to address these risks, within the realms of assessed forecasting capacities. By leveraging IbF and AA approaches, supported with investments in hazard modelling, the proposed framework could enable timely risk-reducing actions in the face of anticipated GLOF threats.

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List of Acronyms

GLOF – Glacier Lake Outburst Flood

PDGL - Potentially Dangerous Glacial Lake

DRR - Disaster Risk Reduction

WMO - World Meteorological Organization

IbF - Impact-based Forecasting

DRM - Disaster Risk Management

CERF - Central Emergency Response Fund

AA - Anticipatory Action

NDRRMA - Nepal's National Disaster Risk Reduction and Management Authority

FOREWARN - Forecast-based Warning and Analysis Network

EWS - Early-Warning System

RCCC - Red Cross Red Crescent Climate Centre

WoS - World of Science

UNDP - United Nations Development Programme

EAP - Early Action Protocol

NRCS - Nepal Red Cross Society

R1 – Interview Respondent 01

Table of Contents

1 Introduction

1.1 Background and motivation

A glacier lake outburst flood (GLOF) is a rapid discharge of water from a lake situated at the side, front, within, beneath, or on the surface of a glacier (Iturrizaga, 2011). GLOFs are a recognised threat by the Nepali government (Vaidya et al., 2022), with 47 potentially dangerous glacial lakes (PDGLs) assessed to threaten Nepal, 42 of which lie in the Koshi river basin (Bajracharya et al., 2020a; Appendix 1). A transboundary working group for GLOFs has resultingly been established under the 'Koshi Disaster Risk Reduction (DRR) Knowledge Hub' (ICIMOD, n.d.). PDGLs threatening Nepal were recently categorised by Bajracharya et al. (2020a) using criteria depicting outburst susceptibility. Hazard assessments are based off lake and dam characteristics, source glacier dynamics, and surrounding morphologies (ibid.). Globally, many live downstream of susceptible lakes (Carey, 2005), meaning the potential humanitarian impacts of such events are large. In 2021, for instance, Pemdang Pokhari lake outburst in Nepal, with the cascading hazard chain resulting in 25 lives lost, 1000 displaced, and the destruction of 337 residencies, alongside commercial property, and public infrastructure (Maharjan et al., 2021; ICIMOD, 2022). Research on GLOFs is overwhelmingly concentrated on hazard assessments (Emmer et al., 2022). Yet, parallel assessments of vulnerabilities and coping capacities in such contexts are key to complete risk understandings (World Meteorological Organization [WMO], 2017). With more assessments required to understand the Hindu-Kush Himalayan GLOF risk landscape (Vaidya et al., 2019), this study aims in part to highlight some of Nepal's related data gaps.

Humanitarian planning is noted by the Secretary-General's Special Representative for DRR, Mami Mizutori, to lack comprehensive analysis of disaster risks (UNDRR, 2022). Impact-based forecasting (IbF) is one presently underutilised method of proactively assessing disaster impacts to aid preparedness for response, with data deficiencies posing a significant barrier to its operationalisation (ibid.). With the impacts of climate change facing mountain populations especially under-evaluated (McDowell et al., 2019), a need is discerned for risk data to play a greater role in informing humanitarian planning and preparedness activities in mountain regions.

Increasingly, humanitarian practitioners and disaster risk management (DRM) actors are engaging in anticipatory, risk-informed activities to mitigate the impacts felt by disasters (Hultquist et al., 2021; Montier et al., 2022). This growth is paralleled by the emergence of pre-agreed funding arrangements (e.g. Central Emergency Response Fund's (CERF, 2021) Rapid Response fund) for anticipatory action (AA). In line with this global trend, engagement with IbF and AA in Nepal appears to be on the rise. As of 2022, Nepal was one of five active Forecast-based Warning and Analysis Network (FOREWARN) countries, promoting early actions that operationalise 'quality risk information'. Presently, this approach is primarily being piloted for risks associated with flood and landslide hazards in Nepal (UNOCHA, 2022). Nepal's National DRR and Management Authority (NDRRMA, 2021) express a desire to work further with IbF to enhance the effectiveness of their disaster preparedness and response efforts, including the establishment of IbF systems in 36 landslide-prone municipalities. The national disaster information management system - the BIPAD portal - now also includes a module on IbF (Uprety et al., 2022). This cumulatively reflects the shift in Nepal's disaster management focus from largely relief-driven to more proactive DRR strategies (Vaidya et al., 2022).

Fluctuations in lake level and GLOF triggers can theoretically be monitored to anticipate outburst events (Ng and Björnsson, 2003), but localised assessments are generally needed to recognise these triggers and design outburst models that effectively inform DRM (Ng and Liu, 2009; Shrestha et al., 2010). Since monitoring efforts are largely deficient, with many PDGLs lacking any form of early-warning system (EWS), capacities to facilitate early action are compromised (Baigal, 2021). Thompson et al. (2020) particularly stress the lack of institutionalisation of comprehensive GLOF risk reduction in Nepal. It is thus important to assess the potential contributions advanced monitoring and modelling of GLOF risks could bring to preparedness for mountain communities. Risk-informed early action could, for instance, be enabled by using risk data to build triggers to facilitate proactive adaptation practices, like evacuation from GLOF-exposed areas.

'Impact-based' systems enhance capacities to pre-empt the expected development of a humanitarian situation (Choularton, 2007; UNDRR, 2022). IbF thus enables complex risk data to (pre-)inform humanitarian activities (Red Cross Red Crescent Climate Centre [RCCC], 2020). With decision-making stakeholders often bypassed in scientific research, however, risk data are often not well connected to practitioners' operations (Emmer et al., 2022). This provides motivation for the development of a GLOF-specific framework which could ease the translation of risk data into actionable DRM. Synthesising Nepal's GLOF risk data and proposing a preliminary framework could additionally support the National Strategic Action Plan of Nepal to reduce the risk of 7 high-risk glacial lakes by 2030 (Maskey et al., 2020).

1.2 Purpose and research questions

1.2.1 Purpose

This study aims to assess how the development of impact-based forecasts could guide humanitarian response planning and preparedness activities in communities exposed to GLOF risks in mountainous Nepal. By assessing the state of existing risk knowledge as well as how forecast-based actions are applied to other hazard types, this study ultimately aims to illustrate what an IbF system could look like for managing GLOF threats.

1.2.2 Research questions

1. How are glacier lake outburst flood risks to Nepalese communities presented in academic literature?
2. How could impact-based forecasting address glacier lake outburst flood risks in Nepal?

2 Conceptual Clarifications

2.1 Impact-based forecasting

The transition from threshold-based to impact-based systems reflects a shift from simply anticipating a hazard event to utilising exposure and vulnerability data to pre-empt the impacts an event may induce (MHEWC-III, 2022), with the ultimate goal of enabling the timely activation of targeted humanitarian response (Choularton, 2007). Modelling localised impact-based projections using socioeconomic and environmental indicators can ensure a holistic assessment of risks (Green Climate Fund, 2021), and is thus a prerequisite for risk-informed DRM. This approach can guide contingency planning by pre-empting the development of a humanitarian situation through time (CERF Advisory Group, 2019; UNDRR, 2022). Contingency planning involves proactively *"developing strategies, arrangements and procedures to address the humanitarian needs of those adversely affected by crises"* (Choularton, 2007, p.3). This process can help coordinate DRM activities by explicitly outlining responsibilities, resources, information on affected populations' needs, and operational procedures (Knox Clarke, 2022). Anticipated events can thereby be managed more effectively (Alexander, 2005), evading a post-disaster state of deficient response capacities, resources, or plans (Coppola, 2011). Robbins et al. (2022) explore the 'research-to-operational' interface and suggest interpretations of IbF (i.e. level of detail in anticipated impacts) differ between applications.

2.2 Anticipatory action

One way of operationalising the outputs of IbF to mitigate disaster risks is through anticipatory, or 'early', action (Robbins et al., 2022). AA is broadly defined as *"acting ahead of predicted hazardous events to prevent or reduce acute humanitarian impacts before they fully unfold"* (Knox Clarke, 2022, p.7). This ultimately aids preparedness for efficient and effective response to threats by anticipating humanitarian needs (UNOCHA and Start Network, 2022). Understandings of 'early action' terminology differ primarily in two regards (Robbins et al., 2022). First, in the timing of actions; how far in advance of the disaster striking is 'early'? The second point of divergence lies in the degree of planning behind actions. In this study, early actions are assumed to be risk-informed, pre-planned & initiated based on a predetermined trigger, and undertaken in advance of disaster impacts being felt. The terms early/anticipatory action are used interchangeably. The line between preparedness and AA is drawn here such that, while still developing capacities to reduce disaster risks, the former must not necessarily relate to any particular forecast event. There are, still, inherent overlaps.

3 Methodology

A range of data sources informed the analysis of this study via an exploratory, instrumental case approach (Creswell, 2013), using case entities to understand capacities to anticipate GLOF threats and existing IbF applications. Qualitative data was obtained via both semi-structured interviews and social artefacts.

3.1 Research strategies

To answer RQ1, an inductive approach was utilised to clarify the existing state of knowledge on forecast impacts from anticipated GLOF events in Nepal across academic studies. This is justified by the descriptive nature of the question and my desire to collate insights from different data sources to establish commonalities (Blaikie, 2010). A systematic literature review was undertaken and involved collating insights from research papers through keyword searches in Scopus and World of Science (WoS). I present the results according to each focus lake.

To further aid the assessment of how IbF could be used to address GLOF threats (RQ2), interviews were conducted with actors working with IbF and AA. Interviews informed on how IbF/AA are being used for other hazard types. I encouraged my interviewees to reflect on their experiences, aiming to uncover the (tacit) rules and knowledge that govern them (ibid.). This strategy enabled the conceptual reconstruction of actors' accounts and interpretations to address the research problem. A non-systematic review of IbF/AA literature complemented discussions surrounding derived themes. Insights were then correlated with the evolving understanding of the GLOF risk landscape in Nepal gained through the literature review, as well as collated impact data from past GLOF events (Appendix 2). The data were ultimately used to inform a proposed IbF framework for managing GLOF threats.

3.2 Data collection

Data were obtained from a systematic literature review of PDGL risk assessments (PDGLs, with anticipated impacts in Nepal), six semi-structured interviews, and a supplementary content analysis of IbF and AA documents.

The literature review followed Snyder's (2019) guidelines. Risk data on PDGLs with anticipated impacts in Nepal were extracted via a systematic literature review to inform the discussion on the state of risk knowledge for this hazard type. The search thread: TITLE-ABS-KEY (glof AND nepal AND risk OR hazard OR assessment) returned 57 results in Scopus, and the thread: ALL (glof, risk, hazard, assessment, nepal) in WoS returned 24 studies. Of 81 total returns, 14 were duplications, leaving 67 studies to be screened against the eligibility criteria (Table 1). 46 did not fulfil the inclusion criteria, leaving 21 for in-depth analysis. Further search threads were conducted for individual lake names through Scopus, WoS, and Google Scholar, to identify any relevant grey or otherwise unaccounted for literature. Additional studies were extracted from the assessed literature as deemed relevant for inclusion.

Include studies which …	**Exclude studies which …**
Consider downstream impacts (i.e., GLOF modelled; at-risk settlements discussed)	Only look at PDGL expansion or lake susceptibility to outburst; [AND/OR] Only model trigger and/or outburst mechanisms (i.e., no downstream flow model)
Assess a PDGL with anticipated impacts in Nepal	Assess a PDGL with no anticipated impacts in Nepal
Model possible future scenarios	Only model reconstructed GLOF events

Table 1. Eligibility criteria for literature review.

Actors with experience working with IbF/AA in Nepal were the key group targeted for interviews. Purposeful sampling was employed by determining a set of criteria for the actors of interest, selecting representative participants across the IbF/AA space in Nepal to provide insights into the research problem (Creswell, 2013). While most respondents reflected on Nepal-based experiences in AA, one respondent's context of experience was in Pakistan to enable hazard-specific insights in GLOF forecasting. There were accessibility constraints in retrieving all informants of interest, limiting the context of inquiry. The relative homogeneity of the sample suggests further interviews would have had limited drastically new emergent themes (Guest et al., 2006), although Hennink and Kaiser (2022) suggest 9-17 interviews may be appropriate for reaching data saturation. Rubin and Rubin's (2012) 'responsive interviewing model' was followed through a flexible interview sequence approach. An interview protocol, outlining overarching questions, helped frame the discussions (Appendix 3; Kvale and Brinkmann, 2009; Creswell, 2013). Questions/probes were refined throughout the process and varied marginally between interviews. The interviews were conducted through video conferencing software and lasted ~1 hour.

3.3 Data analysis

The aim of my analysis was twofold. First, to illustrate the state of risk information on GLOFs in Nepal. Second, to create a contextualised understanding of how an IbF system could be applied to GLOF hazards. This involved assessing how IbF is presently being used to inform humanitarian activities and planning processes for other hazard types and applying it broadly to Nepal's GLOF risk landscape.

To achieve these aims, a content analysis approach was adopted (Wieringa, 2014). Interviews were recorded and transcribed for analysis purposes. To analyse transcribed interviews and documents I used MAXQDA to organise my data and notes (Creswell, 2013). To reduce data into an analysable format, I coded concepts and key themes from the raw data, subsequently categorising them into more abstract conceptual groupings (Blaikie, 2010). An iterative coding approach was adopted, as I conducted data collection and analysis in parallel. This 'constant comparative method' of analysis (Glaser and Straus, 1967, in ibid.) helped in the identification of connections between evolving categories, unveiling *"regularities, variations, and singularities"* in the data (Dey, 1993, p.152).

The derived codes/categorisations helped develop 'thick' descriptions of my cases and research problem. These categories were aggregated to illustrate the meanings derived from directly interpreting isolated codes (Blaikie, 2010). Targeted analysis of the contextual elements and social actors enabled a deeper understanding of the cases, and triangulating data sources increased the validity of interpretations drawn (Creswell, 2013). Since the coding classifications were subjectively directed by the overall research process and personal biases (Blaikie, 2010), interpretations made throughout were documented to maintain consistency (Wieringa, 2014).

4 Part 1: The state of risk data for GLOFs in Nepal

This section describes the state of GLOF risk data by synthesising the published risk information on Nepal's PDGLs. The below-listed categories are used to present the results of the literature review. These are elements recorded across the assessed literature that relate principally to the dynamics of, impacts associated with, and degree of certainty surrounding forecast GLOF events, thereby helping address the research questions. Those not explicitly covered in all reviewed studies are included in the final column of the results tables. Each elements' relevance to the research questions will be further clarified as the associated data is unpacked.

- Are lead times identified?
- Are multiple scenarios considered and modelled?
- Are exposed settlements quantified or mapped?
- Is future lake evolution anticipated?
- Were assessments conducted in-field?

4.1 Nepal's potentially dangerous glacier lakes

Seven Nepalese lakes are described in detail, followed by subsections for the remaining data, including transboundary threats. The greater attention paid to these lakes is not to suggest other lakes should be considered secondarily, only that they have attracted a greater level of assessment in the reviewed literature.

4.1.1 Existing risk data and GLOF models

Lower Barun Lake

This lake is the largest of Bajracharaya et al.'s (2020a) classified PDGLs in Nepal. Maskey et al.'s (2020) outburst scenarios calculate peak discharges and lead times for settlements downstream (e.g. Yangle Kharka - 9km/3h; Barun Bazaar - 32km/4h). Sattar et al.'s (2021) 'extreme magnitude scenario' produces a lead time of 1.1h for Barun Bazaar, with three lower magnitude scenarios ranging up to 6.5h. Impacts to life and property are anticipated at Yangle Kharka, with the trekking trail to Makalu base camp also lying in the outburst path (Maskey et al., 2020). High flood heights are modelled 20-30km downstream, but there are limited settlements in this reach in Makalu Barun National Park (ibid.). Additional at-risk sites named by Gurung et al. (2021) include Pemathang, Gola, and Arun III hydropower Project. An earlier assessment by Rounce et al. (2016) anticipate 640 buildings and 5.9km^2 of agricultural land were at risk. Koirala and Saraswati (2021) assess impacts downstream up to the Makalu Rural Municipality boundary but primarily focus on anticipating economic losses. The Barun-Arun valley, where this lake is situated, *"is not equipped with any mitigation measures to counter* [GLOF] *threats"* (Sattar et al., 2021, p.19).

Study	Lead time recorded	Number of scenarios	Exposed settlements	Future lake evolution considered	In-field / remote	Additional notes
Sattar et al. (2021)	Yes	8 low-to-extreme magnitude GLOF events modelled	Mapped & quantified (mapped inundation limits for each scenario)	Yes (4 GLOFs modelled under future lake growth)	Both (field-assessment of lake bathymetry)	Study stresses limitations in the model and potentially-influential unmodelled parameters. Models 2 avalanche scenarios into the lake. Physically-based hydrodynamic model.

						Analysis of flow hydraulics in 6 settlements. Cascading hazard triggers not considered (e.g. GLOF spilling from Upper Barun Lake).
Gurung et al. (2021)	No	4 (only peak discharge assessed)	Potentially at-risk settlement sites named	No	Both (field-assessment of lake bathymetry)	Study notes discrepancies in calculated peak discharge for different breach scenarios to Maskey et al. (2020) due to different lake volumes used.
Maskey et al. (2020)	Yes	1	Mapped inundation zone; number of affected settlements not quantified	No	Remote	Study uses a 2D physically-based hydrodynamic model, modelling 100km downstream. Models 'most-likely' (20m breach) scenario of 4 peak discharge scenarios calculated for different breach heights.
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (not modelled)	Remote	Not a physically-based hydrodynamic model. Noted model limitations: no field assessment of moraine composition to assess breach dynamics.

Thulagi Lake

A GLOF from Thulagi was most recently modelled by Maskey et al. (2020). The settlements of Dharapani, Tal, Syange, and Bahundanda village are projected to expect flood arrival times of 2.5h, 3h, 4h and 4.5h respectively. Rounce et al.'s (2016) earlier model suggests 754 buildings lie in the outburst path and while Khanal et al. (2015a) also anticipate high downstream impacts they recommend a "*two-dimensional physically based model*" would better quantify risks. The only indication of assessed impacts in Maskey et al.'s (2020) model, however, is that flood height in Tal village would be ~14.9m, submerging low-lying settlements and land. An estimated 165,068 were assessed by ICIMOD (2011) to be affected by a 'loss of resources' should this lake flood, although it is uncertain what is encompassed in being 'affected' in this study. According to Khanal et al. (2015a), no DRM measures had been put in place for Thulagi, despite a demand from an exposed settlement downstream (Tal). Hazard assessments suggest peak monsoon rainfall has not yet caused Thulagi to overflow, but drainage patterns and dam stability should be monitored (ICIMOD, 2011).

Study	Lead time recorded	Number of scenarios	Exposed settlements	Future lake evolution considered	In-field / remote	Additional notes
Maskey et al. (2020)	Yes	1	Mapped inundation zone; number of affected settlements not quantified	No	Remote	Study uses a 2D physically-based hydrodynamic model, modelling 100km downstream. Models 'most-likely' scenario (20m breach) of 4 peak discharge scenarios calculated for different breach heights.
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (but not modelled)	Remote	Not a physically-based hydrodynamic model.
Khanal et al. (2015a)	Yes	1	Mapped & quantified	No	Both (in-field focus-group discussions of exposed elements)	Secondary effects considered (impacts beyond inundation zone). Lead time conflicts Maskey et al. (2020). Undertook 12 group discussions in the Marsyangdi Basin to assess impacts.
ICIMOD (2011)	Yes	1	Mapped & quantified	No	Both	1D hydrodynamic model. Additional scenarios considered with no flood simulated.

Imja Tsho

One settlement area downstream of Imja Tsho is Dingboche. Somos-Valenzuela et al. (2015) suggest a 1h arrival time for a GLOF from Imja here, with a range of 0.6-1.9h. In Ghat near Phakding, a 3.1h lead time was assessed (range 2.4-4.4h) (ibid.). Bajracharya et al. (2007a,b) estimate flood arrival times of 14/46 minutes for the respective settlements. Bajracharya et al.'s (2007b) assessment is limited to anticipating lead times, with little regard for impact to downstream settlements. Some anticipated impacts are vaguely suggested, such as parts of Dingboche village being vulnerable to secondary impacts (i.e. "*lateral erosion at the outer bend of the river*") from a GLOF but "*low possibility of a direct impact*" is anticipated given its elevated position (ibid., p.89). Somos-Valenzuela et al.'s (2015) quantified impacts include the destruction of parts of the main trekking trail from Namche Bazar to Lukla and the inundation of ~9.4ha of farmland and 29 structures in Dingboche. Trail village houses and fields are also identified in projected inundation zones (ibid.). ICIMOD's (2011) modelled flood scenario suggests 360 households inhabit the total anticipated inundation zone. Even in the presence of (modelled) risk mitigation measures, outburst risks are suggested to remain (with

<20m lake lowering), with such measures requiring maintenance and risking weakening the dam itself (Somos-Valenzuela et al., 2015).

Lala et al. (2018, p.3721) generate GLOF hazard maps downstream of Imja which conflict earlier assessments with "*neither modelled case result[ing] in flooding outside the river channel at downstream villages*", asserting negligible risk within settled areas; similar lead times were simulated, however. The models established by Bajracharya et al. (2007b), Somos-Valenzuela et al. (2015), and Shrestha and Nakagawa (2016) are discounted by Lala et al. (2018) for modelling outburst dynamics they deem 'unlikely'. Inhabitants of Chaurikharka, Khumjung, and Namche downstream, however, believe the risk of Imja's outburst to be an adaptation priority (Watanabe et al., 2016).

Study	Lead time recorded	Number of scenarios	Settlement exposure	Future lake evolution considered	In-field / remote	Additional notes
Lala et al. (2018)	Yes	2	Inundation zone mapped, no exposure data	Yes	Both	Study rejects modelled outburst mechanisms of past assessments. Models avalanche-generated impulse waves and the associated process chain using BASEMENT. Accounts for hydrodynamic flow and sediment transport.
Cuellar and McKinney (2017)	Yes	4	Mapped & quantified	No	Both	Thorough exposure assessment – inventory of building types, number of occupants, and periods of occupation. GLOF scenarios originally calculated by Somos-Valenzuela et al. (2015). Full moraine collapse ('worse-case' scenario) used for damage analysis. Limited model extent downstream due to low-resolution DEM.
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (but not modelled)	Remote	Not a physically-based hydrodynamic model. 30m DEM resolution.
Shrestha and	Yes	2	Mapped & quantified	No	Both	65km downstream modelled.

Nakagawa (2016)						3 key sites considered.
Somos-Valenzuela et al. (2014; 2015)	Yes	4	Mapped & quantified	No	Both	Study models 4 lake lowering scenarios. Water and debris flow modelled using FLO-2D.
Khanal et al. (2015a)	Yes	1	Mapped & quantified	No	Both (focus-group discussions of exposed elements)	Secondary effects considered (beyond inundation, e.g. slope undercutting). Undertook 23 focus group discussions in the Dudhkoshi Basin to assess impacts.
ICIMOD (2011)	Yes	1	Mapped & quantified	No	Both	1D hydrodynamic model. More scenarios considered but no flood simulated.
Bajracharya et al. (2007a,b)	Yes	1	Mapped & described	No	Remote	1D hydrodynamic model provides first-pass assessment of impacts.

Tsho Rolpa

ICIMOD have an online visualisation tool for three breach scenarios (10/20/30m) from Tsho Rolpa given the present-day lake level, overlaying socio-economic data with inundation maps (Chen et al., 2021a,b). Downstream along the Rolwaling River lie the villages of Na, Beding, Chhimu, Randing and Nimare, meeting Chetchet Village near the confluence with Tamakoshi River. Another 11 villages lie along Tamakoshi River until reaching Manthali Town (Chen et al., 2022). The worst-case scenario considered in Chen et al.'s (2022) study anticipates the inundation of 1647 buildings and 123 key facilities, impacting 5038 people. Rounce et al.'s (2016) earlier model suggests 2787 buildings, 7.8km^2 agricultural land, and 35 bridges are exposed. Shrestha and Nakagawa (2014) anticipate 733 households (3,939 inhabitants) to be at risk in the Rolwaling and Tamakoshi valleys (up to ~65km downstream at Nayapul village), though this is not based off a precise exposure assessment. Additional impacts downstream of Nayapul are projected, potentially partly explaining discrepancies in exposed assets between studies. ICIMOD's (2011) assessment predicted flood arrival times of 0.79h for Beding, while Chen et al. (2022) predicted 0.45h.

Risk mitigation measures in the form of lake lowering and an EWS were earlier established, yet the risk of outburst remains due to deficient upkeep (ICIMOD, 2011). The main risk here is suggested to be posed by overtopping of the dam by mass movements into the lake (ibid.).

Study	Lead time recorded	Number of scenarios	Exposed settlements	Future lake evolution assessed	In-field / remote	Additional notes
Chen et al. (2022)	Yes	3 (out of 12 considered)	Mapped & quantified	No	Both	Associated datasets: Chen et al. (2021a); (2021b). Online model.
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (but not modelled)	Remote	Not a physically-based hydrodynamic model.
Khanal et al. (2015a)	Yes	1	Mapped & quantified	No	Both	Secondary effects considered (impacts beyond inundation zone). 16 focus group discussions in the Tamakoshi Basin for Tsho Rolpa.
Shrestha and Nakagawa (2014)	Yes	4	Mapped & roughly quantified	No	Both	Study models moraine dam failure via both seepage and water overtopping. Acknowledge missing input parameters.
ICIMOD (2011)	Yes	1	Mapped & quantified	No	Both	1D hydrodynamic model. More scenarios considered with no flood simulated.

Chamlang North Tsho

The most recent study found outlining relevant outputs for this lake was Rounce et al. (2016) whose model anticipates 244 buildings and 2.5km^2 of agricultural land lie in the inundation zone.

Study	Lead time recorded	Number of scenarios	Settlement exposure	Future lake evolution considered	In-field / remote	Additional notes
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (resulting GLOF not modelled)	Remote	Not a physically-based hydrodynamic model.
Byers et al. (2013)	Yes	1	Labelled; no inundation map, only flow depth.	No	Remote	1D unsteady flow model (HEC-RAS). Limited inundation mapping capacities due to insufficiently high-resolution DEM data.

Chamlang South Tsho

Assessments of this lake have, as with the others, stood in disagreement, with resulting implications for capacities to adequately assess the associated risks. Two key studies differed in their assessments of GLOF susceptibility: Byers et al. (2013) and Lamsal et al. (2016). The former purports low chance of outburst, with the latter disagreeing with the terminal moraine's susceptibility to failure. The immediate 45km downstream is noted to be largely uninhabited, except for the presence of "*temporary huts along the river valleys during the pre- and post-monsoon seasons for grazing*" commuters (Lamsal et al., 2016, p.418). The presence of several settlements further downstream along the assumed outburst path are highlighted by an assessment of some neighbouring lakes (ibid.; Khanal et al., 2009). Rounce et al.'s (2016) study quantifies the risk to downstream communities through their model, with 228 buildings and 2.5km^2 agricultural land assessed to be at risk. They suggest, however, that a physically-based GLOF model is needed to more accurately assess risks from this lake. Detailed field surveys are necessary to complete risk understandings here since projected impacts are likely not accurately quantified. Lamsal et al.'s (2016) study named potential at-risk settlement sites, but individual settlements were neither mapped nor quantified.

Study	Lead time	Number of scenarios	Exposed settlements	Future lake evolution considered	In-field / remote	Additional notes
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (but resulting GLOF not modelled)	Remote	Not a physically-based hydrodynamic model.
Byers et al. (2013)	Yes	1	Labelled; no inundation map, only flow depth.	No	Remote	1D unsteady flow model.

Lumding Tsho

Detailed risk assessments are lacking for this glacial lake, despite its expanding nature and potential for overtopping following ice avalanches or input from upstream lakes (Rounce et al., 2016; Lala et al., 2018; Khadka et al., 2019). Rounce et al.'s (2016) model anticipates downstream impacts felt by 184 buildings and 2.0km^2 of agricultural land.

Study	Lead time	Number of scenarios	Exposed settlements	Future lake evolution considered	In-field / remote	Additional notes
Rounce et al. (2016)	No	1	Mapped & quantified	Yes (resulting GLOF not modelled)	Remote	Not a physically-based hydrodynamic model.

Other Nepalese lakes

Rounce et al. (2017) present spatially limited, non-physically-based, hydrodynamic models for several additional PDGLs; these are not discussed further given the model limitations and absence of supplementary assessments. Beyond this, no further lakes have aligned models fulfilling this study's inclusion criteria.

Some smaller lakes typically excluded from PDGL classifications are noted by numerous studies to pose a potentially under-accounted for risk, with devastating impacts resulting from previous outbursts (e.g. Byers et al., 2020). Smaller supraglacial ponds can serve as precursors for future lake development, while also having the potential for large outburst volumes where floodwaters are supplemented by en/sub-glacial conduit water stores (Chand and Watanabe, 2019). Risk data on this lake type appears limited across Nepal, with morphological studies of glaciers required to understand likely outburst dynamics (ibid.). Kropáček et al. (2015) is one study reporting on seasonal supraglacial lake development and past events threatening the Nepalese village of Halji.

Besides pro- and supra-glacial lakes, risk data similarly appear to be limited for surge-type glaciers. Fischer et al. (2023) note the potential for outburst floods associated with surge-type glaciers in the Seti Khola catchment, but no further assessments were identified.

Transboundary Lakes

Tibet hosts 25 PDGLs that are anticipated by Bajracharya et al. (2020a) to have transboundary impacts in Nepal. The transboundary Koshi River Basin is recognised by many studies as particularly GLOF-prone, with PDGLs in both Nepal and Tibet (Vaidya et al., 2022).

From Tibet, transboundary threats from glacier lakes to Nepal are suggested to be greatest in the central Himalayan counties Nyalam, Jilong, and Dingri (Allen et al., 2019). Allen et al.’s (2019) assessment suggests large communities are situated along the modelled outburst paths from Nyalam county on the Nepalese side, but impacts are not quantified. Allen et al. (2022) further outline a risk to Nepalese communities along the Bhote Koshi river, but their models are not simulated beyond the border. Shrestha et al. (2010) model 30 outburst scenarios from Lumichimi lake, presenting the ‘most realistic four’. Inundation maps are complemented by socioeconomic field assessments in the Nepalese part of the basin. Around 900/2600 households are projected to be affected in their low/high-case scenarios respectively. Khanal et al. (2015a) further held 10 focus-group discussions in the Bhote-Sun Koshi Basin downstream of Lumuchimi.

Khanal et al. (2015b) model two GLOF scenarios along Bhote-Sun Koshi River to Dolalghat in Nepal based off 1) the flood inundation level resulting from Zhangzambu Lake’s outburst in 1981, and 2) 10m higher than in 1981. The forecast impacts are thus not based off volumetric lake assessments. Impacts projected in Nepal for the larger scenario include 3000 households, 170ha cultivated land, 30 public buildings, 58km of roads/trails, 30 bridges, and 3 hydropower projects. At-risk persons were included in the identification of exposed elements.

4.1.2 Discussion of PDGL risk data

The literature review suggests detailed risk assessments are scarce among Bajracharya et al.’s (2020) PDGLs. Of the 47 they classify as posing risks to Nepal, only four are found here to have outburst models quantifying projected impacts using physically-based hydrodynamic models. PDGLs classified according to different susceptibility criteria would be assumed to follow a similar trend given the observed deficiency of risk assessments in this study’s context of inquiry. Byers et al. (2013) affirm the higher uncertainty when using non-physical models to anticipate GLOF inundation extents. While simple flow models can roughly assess inundation depths or lead times (ibid.), producing non-reflective outburst scenarios could have negative implications for effective applications of IbF. The observed deficiency in holistic assessments is assigned in part to the site-specific data (and intensive processes) required to model triggers, breach mechanisms, as well as the flood itself (Rounce et al., 2016). Conflicts in assessments of outburst susceptibility may further fuel this deficiency. Byers et al. (2020), for instance, note a lack of studies in the eastern Kanchenjunga region, pointing to Nangama, a lake experiencing an outburst in 1980, assessed by Rounce et al. (2017) as potentially dangerous but discounted by Bajracharya et al. (2020).

The most recent GLOF simulations for Chamlang North Tsho, Chamlang South Tsho, and Lumding Tsho were conducted by Rounce et al. (2016). Considering these are not physically-based models, conflicts have been identified with assessed impacts for other lakes (e.g. Tsho Rolpa – Chen et al., 2022), and lake conditions may have changed since 2016, the existing risk data likely misrepresents the risk landscape. Chamlang North Tsho additionally had no bathymetric survey at the time of Rounce et al.'s (2016) study further limiting model capacities. The most extensively studied lake appears to be Imja Tsho, likely reflective of the United Nations Development Programme (UNDP)'s (2013) interest in conducting risk reduction activities there.

Inconsistencies between reports' modelled outputs appear high for multiple lakes (e.g. Lower Barun, or Imja Tsho), primarily resulting from different lake or trigger parameters being input into models. Assumptions regarding possible trigger mechanisms is a point of contention for Imja Tsho, where Lala et al. (2018) suggest previous assessments assume unlikely (self-destructive) breach scenarios (piping/seepage). Their assessment assesses only avalanche-induced waves as a GLOF trigger, justified by the lake's lateral moraines posing low risk of failure (ibid.). The implications of such contentions for GLOF prediction capacities will be discussed in section 5.2.

Breach mechanisms for GLOFs commonly include wave overtopping or mechanical failure of the dam (Westoby et al., 2015). Most studies here assess only one 'type' of breach mechanism, but some model multiple possible scenarios within this (e.g. different breach heights over the lake dam – Maskey et al., 2020). Studies running multiple breach depth simulations highlight the differences in impacts felt, with Chen et al. (2022) anticipating 280/1647 inundated buildings under Tsho Rolpa's 'least-serious' and 'worst' modelled cases respectively. Breach type is also shown to have implications for downstream impacts (e.g. Lala et al., 2018). Another point of noted inconsistency is in projected flood arrival times (e.g. for Lower Barun). Cross-correlating model parameters against projected impacts could thus illuminate drivers behind divergent risk data, clarifying the range of viable future scenarios under different GLOF triggers.

Models appear limited spatially in their projected outburst paths, often constrained to distances shorter than where impacts have been felt in past events. Concentrated in the upper river reaches, models may underestimate exposed settlements, exacerbating a lack of risk awareness among distant downstream communities (e.g. Khanal et al., 2015a,b; Rounce et al., 2017). The importance of modelling maximum possible GLOF trajectories is also recognised by Mal et al. (2021, p.2). In some models, secondary impacts beyond the inundation zone are considered (e.g. slope failure in Khanal et al. [2015a] for Imja/Thulagi), based off observations that past GLOFs have induced riverbank instability ~35m from the channel. Yet, overall, the consideration of multi-hazard cascading risks is limited.

The impacts associated with future lake evolution are not considered in the majority of GLOF models reviewed, despite studies that do noting the influence lake expanse and associated shifts in dominating triggers have on anticipated patterns of outflow (e.g. potential for increased exposure to wave initiation from mass wasting – Lala et al., 2018). Anticipating future lake evolution could thus partly account for the dynamic nature of GLOF risk, by forecasting potential future triggers which may not currently control outburst susceptibility (Haeberli et al., 2017; Clague and O'Connor, 2021).

For GLOF risk assessments to be useful decision-making tools, transparent communication of model limitations and possible emergent futures will likely be key. Comparing conflicting outputs across studies is also suggested important for communicating uncertainties. However, limited data from past events and the relatively infrequent nature of GLOFs creates difficulties in judging relative model performance (Rounce et al., 2016). Scientific disagreement concerning trigger types and associated risks is thus likely to persist (Haritashya et al., 2018).

5 Part 2: An IbF framework for GLOFs

Although it is well-established that simplistic hazard warnings may have limited contributions to preparedness, what is less clear is how IbF could inform early actions and response planning for sudden-onset hazard types, especially where high uncertainty in forecasts exists. This section collates the insights gained from existing GLOF risk assessments with applications of AA to other hazard types to propose a framework for managing GLOF risks. The subsections follow the framework's structure, with the ensuing points of discussion derived from the interview coding and categorisation process. The key codes derived from analysing the interview transcripts are presented diagrammatically in Appendix 4, with the emergent themes comprising: working with uncertain and dynamic IbF data, and (developing community capacities while) preparing to operationalise forecasts.

> *"Apart from monsoon, flood, and cold waves … we don't have much* [of a] *habit of anticipating hazards and loss and damage* [in Nepal]*."* (Interview Respondent [R]2)

This quote, taken from an interview respondent, illustrates the observation that AA is in its early stages of application in Nepal. The outputs of the employed non-systematic review of IbF and AA documents are integrated throughout this section to complement the insights gained from the interviewees with applications outside Nepal. The hazard types targeted by interview respondents here include (monsoon) flooding, landslides, and cold waves. Despite Nepal's initial focus on flood hazards, interest among early action practitioners to address and develop frameworks for other hazard types has recently progressed alongside attempts to enhance forecasting capacities (Anticipation Hub, 2023).

5.1 Developing a framework

This section explains the process and motivation behind the development of a GLOF-specific framework. Motivation was taken from the general understanding emerging from the analysis of collated data that *“we need to think differently for [different hazard types] in terms of how anticipatory action is defined and understood conceptually”* (R5). The framework’s structure draws inspiration from existing approaches for other hazard types (e.g. dividing it into two phases; Gettliffe, 2022), taken from both the interview insights and AA document analysis. It is presented as such to provide a guiding structure for practitioners wishing to commence AA activities for this hazard type.

5.1.1 Presenting the preliminary framework

Here an initial draft of a GLOF IbF framework is presented. In the following sections its various elements are unpacked and discussed.

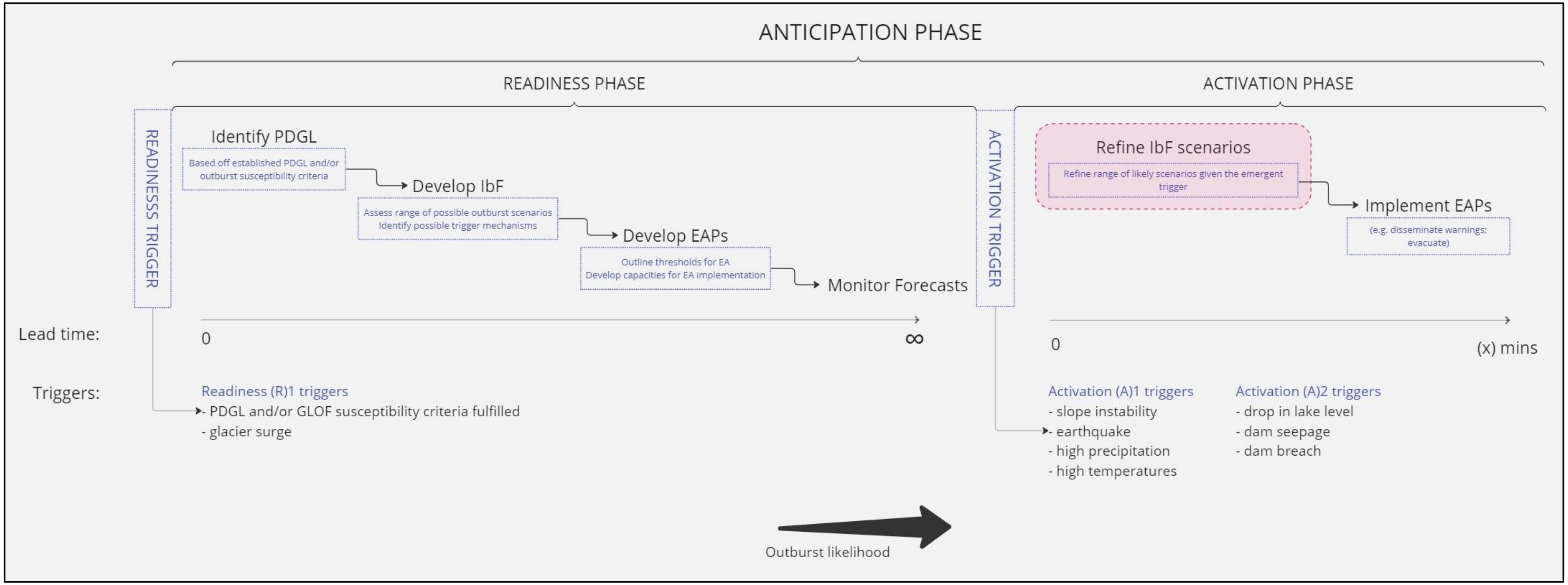


Figure 1. Proposed impact-based forecasting (IbF) framework for GLOFs. PDGL = potentially-dangerous glacier lake. ∞ symbolises that the readiness phase may never reach the activation phase; '(x) mins' indicates the lead time is lake-specific and identified during forecasting. The proposed trigger categories are divided into R1 (outburst susceptibility criteria fulfilled), A1 (outburst likelihood increased), and A2 (imminent outburst evident). The identified triggers are only examples, which could be expanded upon. R1 triggers initiate IbF and early action design processes (conducting/updating); A1/2 triggers activate early action protocols (EAPs) and should be aligned with predetermined scenarios. The red box indicates that capacities and time available to refine scenarios may not exist in every case.

This framework divides the anticipation phase into two parts, a readiness phase, and an activation phase. The readiness phase is activated upon identifying a PDGL. It comprises the period for developing capacities to initiate risk-mitigating early actions. The activation phase is the period between observing a short-term trigger indicating an imminent GLOF threat and impacts being felt downstream. This is the period available for activating (lifesaving) early actions as outlined in the early action protocol (EAP) (e.g. evacuation; risk information dissemination). The range of early actions will ultimately depend on the needs of at-risk persons and available lead times. A1 triggers may provide a greater lead time for renewing the forecasting process to redefine likely emergent scenarios. The A2 trigger-type has noted similarities to Gettliffe's (2022) 'observational trigger' for dry-spells, since the hazard's occurrence itself acts as the trigger, but differs in that actions should be implemented before any shock-related impacts are felt.

Shorter-term forecasts should be catered to more lake-specific parameters which can be unpacked through assessments of potential trigger and outburst mechanisms (section 5.2). The framework thus works on the assumption that activation triggers can be developed and monitored for PDGLs to advance present long-term susceptibility forecasting capacities. Forecasting impact specificities is noted to be possible following the proposed readiness triggers, but there will likely be a range of possible scenarios which can be aligned with the more refined activation triggers. This framework thus enables the incremental addition of dynamic risk information to improve forecasting capacities systematically alongside the emergence of predefined triggers indicating enhanced outburst likelihood.

5.2 Predicting the event: GLOF triggers

The insights gained from actors applying IbF lead to a recognition of a need for an evaluation of forecasting capacities to assess how IbF could be used to address GLOF risks in Nepal. The GLOF literature from the review in part one was thus revisited to extract capacities in prediction. This section discusses the proposed 'readiness' and 'activation' triggers of the framework in relation to GLOF prediction capacities. The former relates to PDGL classification criteria and associated susceptibility parameters. The latter is used to predict an imminent GLOF event based off a (predefined) threshold being met. The assessed range of possible modes of prediction for GLOFs in Nepal are presented under these two overarching categories.

PDGL assessments work with criteria to predict a lake's outburst susceptibility, but capacities to predict precisely when a GLOF will occur presently appear limited in Nepal. Previous studies have divided outburst triggers into dynamic events and self-destruction (e.g. Rounce et al., 2016). This has implications for available approaches to monitoring PDGLs, where on the one hand short-term alerts could be created for triggers like mass movements or high rainfall, while the more complex, long-term degradation processes may be less indicative of an exact point of failure and harder to monitor as individual triggers. While not enabling precise prediction of outburst, these longer-term processes (e.g. melting ice cores in moraine dams; Emmer and Cochachin, 2013), could be indicative of a lake's increased *potential* for a particular mode of outburst.

Although the importance of conducting individual lake assessments to identify the contextualised range of possible outburst triggers is emphasised, Clague and O'Connor (2021, p.487) broadly suggest monitoring high-risk lakes to assess signals of impending GLOF events through:

Remote mapping of lakes	*Inspecting dam seepage*	*Assessing moraine dam ice cores*
Monitoring adjoining slope instability	*Measuring water inflow to lakes*	*Observing signs of instability in neighbouring ice masses*

5.2.1 Readiness triggers

Proposed here are some parameters which could be useful for monitoring long-term GLOF susceptibility, triggering the first stage of assessment for any identified PDGL. While broadly aligned with established GLOF susceptibility criteria, their framing as readiness triggers could more systematically enable targeted risk-reducing strategies.

As Bajracharya et al. (2020a,b) have the most recent, holistic assessment of Nepal's PDGLs, this is proposed as one (preliminary) long-term forecasting tool to target areas to initiate the readiness phase. Additional 'readiness triggers' should be utilised to account for the dynamic nature of outburst susceptibility and non-classified potentially dangerous lakes, such as those related to the GLOF susceptibility criteria presented by GAPHAZ (2017, Appendix 5). In the absence of a GLOF event at any given lake, assessments could be renewed after a set period to redefine the risk landscape, following NDRRMA's (2022) general guidance for AA in Nepal. Alternatively, any significant change in the nature of a pre-identified PDGL and/or its surroundings (e.g. upon lake retreat into a preidentified avalanche runout zone) could trigger updated readiness phase processes.

Surge-type glaciers were discussed briefly in part one and relate to the formation of ice-dammed lakes caused by a surging glacier blocking a water outlet's natural course (Hewitt and Liu, 2010). This trigger-type may have limited application or relevance for Nepal; although whether the limited studies discussing this risk is reflective of the 'true' risk landscape, is uncertain. The use of a surge-type event as a monitored GLOF trigger was discussed by interview respondent (R3) who has experience monitoring GLOF threats in Pakistan.

5.2.2 Activation triggers

To advance the present state of risk knowledge, site-specific assessments are encouraged during the readiness phase to facilitate more precise monitoring of a lake's enhanced potential for outburst via defined 'activation triggers'.

The risk assessments studied here model an array of trigger and outburst mechanisms that could theoretically be observed at each PDGL to assess the likelihood of imminent outburst. These broadly include, but are not limited to, mass movement-induced wave overtopping, and moraine seepage. Literature beyond that included in this study may be useful to inform further on site-specific outburst triggers (e.g. Watanabe et al., 2009; Shrestha et al., 2013), since this was not a key research focus and individual GLOF risk models do not appear to commonly consider the full array of potential trigger mechanisms. However, for most PDGLs in Nepal, it is assumed these are yet to be thoroughly assessed and modelled even outside of the studied literature. Filling knowledge gaps in localised outburst trigger mechanisms is thus suggested as a key research priority for enabling operational IbF in Nepal.

Clague and O'Connor (2021) suggest moraine dams generally fail by wave-overtopping and associated incision processes. Lower Barun lake is assessed by Sattar et al. (2021) to be susceptible to GLOF-triggering mass movements given the surrounding steep slopes and hanging ice masses. Nangama lake is noted to be liable to a similar set of triggers (Byers et al., 2020). One way of monitoring a lake's susceptibility to overtopping could thus be monitoring instability indicators (e.g. permafrost melt) on surrounding slopes, which could be indicative of an increased potential for mass movement into the lake (ibid.). Fecht and Orlove (2020) additionally propose utilising seismic data to monitor slope instability. Although mass movement appears a common trigger for wave-overtopping across the Himalayas, related triggers include heavy precipitation or strong winds (Nie et al., 2018; Clague and O'Connor, 2021).

Although high temperatures and precipitation have been correlated with previous GLOF occurrences (Allen et al., 2016b; Chen et al., 2023) and studies suggest observing such parameters to assess GLOF risks (Chen et al., 2017), no risk assessments analysed in this study explicitly model climatic conditions as monitorable trigger parameters. The potential for using climatic data to anticipate GLOF threats is, however, exemplified by the heatwave monitoring-induced contingency planning before the recent Shisper GLOF, Pakistan (Tariq, 2022). Since this appears a relatively isolated example (Baigal, 2021), the possibility of developing forecast-based temperature thresholds in Nepal remains uncertain. It is nonetheless proposed temperature thresholds could trigger early actions like reassessing ice-core or permafrost degradation processes and related risks. Localised stations would likely be required to monitor this parameter given mountain environments' microclimatic variations (Vaidya et al., 2019).

Byers et al. (2022) discuss earthquakes as a potential trigger of both moraine dam instability and mass movements into susceptible lakes. The only observed GLOF directly correlated with the infamous 2015 earthquakes that shook Nepal was Dig Tsho (Byers et al., 2017). Carey et al. (2021) note the seismically-induced calving at Imja and Tsho Rolpa in 2015, with the associated displacement wave hazard reportedly mitigated by the temporarily-frozen lakes, suggesting a potential (seasonally-dependent) trigger related to seismic activity. The potential for seismic activity to act as a GLOF trigger in the Nepalese Himalaya does not appear to have been extensively assessed in the reviewed literature, except for Chen et al. (2023) logging its potential to exacerbate impacts by providing sediment input into outburst flows downstream. Maharjan et al. (2021) further stress the scarcity of research relating seismicity and moraine-dam stability.

The cascading hazard of supra/en/sub-glacial conduit collapse is noted by Haritashya et al. (2018) to increase hydrostatic pressures in proglacial lakes resulting in a GLOF. Lower Barun and Imja-Lhotse Shar are two examples of glaciers with supraglacial lakes with recognised GLOF potential (ibid.). To contribute to GLOF prediction, modelling such hazard chains and determining a monitorable trigger would demand significant investment in knowledge-generation for localised glacio-hydraulic processes.

The identified gaps in short-term prediction capacities ultimately appear to be a result of a lack of investment in assessing trigger mechanisms at individual PDGLs. Without site-specific assessments and ongoing monitoring, the capacities of downstream communities to respond to GLOF events through AA will thus be restricted. In some of the assessed cases, there is already a baseline for trigger development (e.g. Allen et al.'s [2022] GLOF susceptibility indicators for three PDGLs in Poiqu basin). However, the deficiency of uncovered risk data suggests this is not the case for most PDGLs. Monitoring A2 triggers will likely demand less scientific investment than A1. A dramatic drop in lake level, for instance, could indicate immediate risk of impact from outburst, observed using simple monitoring equipment such as video cameras and/or water-level recorders (Clague and O'Connor, 2021). Although aligned with greater certainty of outburst, the shorter associated lead times could limit the potential for early action.

5.3 Classifying lead times

Insights into applications of AA for other hazard types suggest lead times have implications for the range of available early actions. It is thus inferred a prior awareness of lead times is key to informing EAPs for GLOFs. Lead time is defined here in two ways. The *onset-impact* lead time being the time between the onset of the GLOF and impacts being felt downstream, and the *operable* lead time being the time between forecasts and the emergence of humanitarian impacts. These forecasts could relate to both the readiness and activation triggers (as shown in Figure 1).

While past GLOFs have seen *onset-impact* timeframes of 5-6 hours (UNDP, 2015), much shorter times are anticipated for some of Nepal's PDGLs, with studies modelling lead times <1h for downstream settlements. Allen et al. (2022), for instance, anticipate a GLOF originating from Tibet would hit the Nepalese border (at Zhangmu) just 28-32mins following outburst. One interview respondent (R3) considered the 10-15min *operable* lead time they had *"ample time"* given the system in place. Since another (R6) remarked a few days was *"very little lead time"*, this perspective is seemingly dependent on the actions desired to be implemented (evacuation versus protecting livelihoods). NDRRMA (2022) state AA should not be restricted to solely life-saving activities. However, when available lead times are on the scale of minutes-hours rather than days-weeks, the range of available early actions following GLOF activation triggers is limited. When considering actions activated by longer-term forecasts, however, there could be room for activities besides evacuation that attend to wider anticipated humanitarian needs and the development of response capacities (e.g. establishing shelters).

Compared to other hazard types this study suggests there could (theoretically) be a relatively clear window for action for GLOFs, at least following the proposed A2 trigger-types. This window relates to the anticipated (*onset-impact*) lead times as suggested by the outburst models. Capacities to accurately forecast lead times, however, remain to be adequately verified for most models assessed in this study, suggesting associated uncertainties could misinform EAPs. GLOF models also emerge with conflicting results on anticipated lead times. Allen et al.'s (2022) assessments of the transboundary risk from Galongco, for instance, differ fundamentally from Zhang et al.'s (2021), with forecast lead times of 0.5h and 2h respectively. Similar differences could be seen for assessments of Imja Tsho, where ICIMOD (2011) reported a lead time of 3.1h for Dingboche, and Somos-Valenzuela et al. (2015) 1h. Clarifying the range of possible lead times could thus be key for effective EAP design, accounting for the emergence of multiple possible scenarios.

One common concern arising from discussions on lead times was a need to account for the time taken to disseminate warnings. This supports the need for preestablished systems for timely information dissemination. The spatial positioning of EWSs is important, especially for transboundary threats where stations situated in Nepal would restrict *operable* lead times (Ives et al., 2010; Allen et al., 2022). While there is no clear cut one-size-fits-all lead time which is adequate for enabling evacuation, R1 stressed "*even one hour or one minute is important in disasters*". This reaffirms the need to maximise the *operable* lead time, by shifting decision-making processes and developing implementation capacities ahead of activation triggers (i.e. during the readiness phase).

5.4 The Readiness Phase

This section deliberates the potential for the long-term anticipation of GLOF-related impacts to enable the implementation of risk-informed preparedness activities during the proposed 'readiness phase'. Actions targeting a forecast GLOF scenario (or set of scenarios) could utilise the outputs of IbF to develop capacities to deliver targeted early actions and response to reduce the anticipated humanitarian impacts. The discussion here will follow the stages as presented in the framework.

5.4.1 Identifying potentially-dangerous glacier lakes

Stage 1 of the readiness phase relates to the identification of PDGLs. This is discussed in section 5.2.1.

5.4.2 Developing impact-based forecasts

Stage 2 of the readiness phase comprises forecasting the impacts associated with anticipated GLOF events. The following areas of discussion mirror the key themes extracted from the IbF/AA practitioner interviews, complemented with insights from wider IbF/AA documents and the afore-presented GLOF literature.

One interview respondent illustrates their perspective on the general aim of IbF as compared to more reactive DRM approaches:

> *"Responding to hazards is different because you already have the event. You already see sufferings, so, you go and just distribute things, you support.* ***But when you are working with prediction, you need to be very clear on your targeting*** *(which areas, which households), and that's where I think an IbF system is important because* ***you try to integrate mixed information into forecasting the impacts of [the] event*** *and that gives you an understanding on what you need to prioritise, where you need to go, where you are investing."* (R5)

When working with impact projections, the type of data collected is thus important since it shapes the priorities in, and beneficiaries of, AA. An approach to collecting impact data proposed by another respondent is to do so with regard for the design of early actions. This aligns with RCCC's (2020, p.27) findings and can be linked to the concept of *'action-based forecasting'* (Coughlan de Perez et al., 2016). Respondent 06 refer to their action-oriented forecasting assessments which identified vulnerable households to develop targeted early warning messaging. To determine what data should feed into IbF, the insights collated here suggest it is important to consider how this data will be used to inform AA (e.g. R5), since non-targeted risk assessments may fail to adequately inform effective DRM measures. The assessment in part one of available risk data for anticipated GLOF events could thus serve as a base for further analysis of available forecast-based actions as well as inspiring forecasting methodologies that are better catered to the design of targeted DRM strategies.

Exposed settlements and anticipated needs

Projecting impacts to settlements was a common theme across respondents targeting monsoon, flood, and landslide hazards in Nepal. Forecasting the number of damaged or destroyed buildings in any given GLOF event is thus suggested as important (e.g.) for addressing immediate or prolonged displacement needs. Using Chen et al.'s (2022) models from Tsho Rolpa, substantial damage is anticipated for 120/900 buildings in the least-severe/worst-case scenarios respectively. This could inform preparedness activities by informing on the anticipated number of people affected, and thus the maximum number of people that may require shelter in the aftermath of an event. However, these numbers are in themselves taken here as inadequate for fully enabling preparedness, given the recognised importance of nuanced vulnerability data. Insights from applications of IbF in Nepal suggest a need for complementary household-level assessments to inform actions, specifically identifying vulnerabilities that may limit individual's adoption of risk-mitigating activities.

> "[We use] *a lot of vulnerability indicators that will help the Community Disaster Management Committees understand there are different levels of needs and that, even within the same exposed areas, we need to target specific households." (R1)*

Humanitarian actors working with AA in Nepal appear to recognise the importance of accounting for individual vulnerabilities and capacities in early action design, especially regarding the mobility constraints of the elderly, persons with disabilities, pregnant women, children, and the landless (Nepal Red Cross Society [NRCS] et al., n.d.). Respondent 01 was keen to emphasise the need to proactively account for vulnerabilities after identifying hazard-exposed areas by "*collecting household level data on socio-economic situations and livelihoods in programme intervention areas*". This sentiment is affirmed in the wider IbF literature, with a foundational understanding that IbF "*enables disaster risk managers to plan for responses that are inclusive of vulnerable and marginalised groups*" (Anticipation Hub, 2022, p.1). NRCS have uploaded 'a geo-referenced household-level database' onto the NDRRMA's BIPAD portal to develop capacities to identify and address intersecting vulnerabilities when developing DRM strategies (Karki et al., 2022). Respondent 02 also discussed the potential for utilising existing social security vulnerability data to avoid repeat data collection processes. However, the importance of considering hazard-specific vulnerabilities is stressed here.

A regard for household-specific impacts is lacking from the majority of PDGL assessments reviewed in this study. Although some quantify the number of exposed households, very few assess household-level socio-economic risk elements. Thus, to develop effective AA for GLOFs, additional vulnerability and capacity assessments would be required downstream of the majority of Nepal's PDGLs to complete IbF capacities. Comparing the risk assessment approaches of Khanal et al. (2015a) and Chen et al. (2022) for Tsho Rolpa, Chen et al.'s remote assessment, while conducted to a higher resolution, is lacking the nuanced focus-group discussion of anticipated impacts run in the former study. Khanal et al. (2015a, p.226) collect vulnerability and capacity data on "*ethnicity, family type, level of education, landholding size, livelihood options, annual income, food sufficiency, …*". Such data could be important for anticipating the needs of disaster displaced persons (e.g. in designing emergency shelter), but as discussed above, might be effective if collected with regard for early action design.

> *"GLOFs not only destroy on the way, they also* [induce] *long-term damage to low-lying areas."* (R3)
>
> *"We were planning for initial response, but the major disaster happens after that, because people lose their land, people lose their properties, houses. You have to plan for that in advance."* (R6)

If working with longer-term impacts is a priority within IbF, as implied by these quotes, insights from past GLOF events and actors working with other hazard types suggest a need for a nuanced focus on affected livelihoods and settlement-related needs. The assessments being conducted in Nepal for landslide hazards, for instance, adopt a long-term forecasting lens despite present capacities in forecast-based action being limited to "*saving lives and providing immediate basic services*", with R1 describing:

> *"The whole assessment itself looks at the longer-term impact of whether the house will be affected, whether their livelihoods, whether the lands would be affected."* (R1)

R5 challenged capabilities to save livelihoods through early actions for sudden-onset events, suggesting activities would primarily be lifesaving. A desire was, however, expressed across some respondents for anticipating livelihood impacts to account for longer-term post-disaster needs. This suggests IbF could be tailored to attend to both EAP design and wider risk-informed preparedness activities.

Working with uncertain and dynamic IbF data

A common issue emerging during analysis of the interview responses was that of working with dynamic and uncertain risk data. The literature review raises this as a pertinent concern for managing GLOF threats, primarily regarding the dynamic nature of the hazard under climate change, with (e.g.) proglacial lakes expanding under glacial retreat (Sattar et al., 2021), or degrading permafrost increasing the likelihood of slope failure and subsequent mass movement triggers (Haeberli et al., 2017). Model uncertainties are noted in the analysis to relate principally to GLOF inundation extents and flood arrival times, with cross-study discrepancies rooted in conflicting understandings of trigger and outburst mechanisms.

Demonstrating the dynamic nature of PDGLs in Nepal, some assessments project the evolution of specific lakes and assess the future risks associated with their expansion (e.g. Allen et al., 2016a; Lala et al., 2018). Assessments across the Himalaya-Karakoram additionally project the formation of thousands of new glacial lakes (e.g. Linsbauer et al., 2016). While future lake expansion and associated outburst hazards can be forecast to an extent (Khadka et al., 2021), GLOF risk assessments should be continuous and non-rigid processes, updated after set periods to account for (uncertainties in) evolving risk landscapes (NDRRMA, 2022; Wassénius and Crona, 2022). Regular monitoring of lakes, as well as their neighbouring ice masses and slopes, is thus suggested to be key to mitigating the risks associated with future outbursts. Chen et al. (2023) additionally note the dynamic nature of GLOF risks associated with loose material produced in the aftermath of earthquakes, stressing the need not only for renewed assessments of lake properties, but also holistic (physically-based) simulations, given the implications increased sediment appears to have for the scale and intensity of flooding. The idea that disaster planning processes serve best when dynamic and adaptive to evolving information is not new (e.g. Perry and Lindell, 2003), but remains to be systematically integrated within GLOF risk management.

The element of human exposure is also dynamic in the Nepal Himalaya and will likely demand continual reassessment. Lamsal et al. (2016), for instance, note that the 45km stretch of the Hongu river from Chamlang South Tsho to its confluence with Dudh Koshi is largely uninhabited apart from the temporary settlement of seasonal grazers. This dynamic exposure would likely best be accounted for by in-field vulnerability assessments as it would likely not be captured by wholly remote studies. Carey et al. (2021) likewise report a rarity in contextual analysis of the dynamic nature of population and infrastructure exposure for cryospheric hazard-types, further stressing the need for such assessments. Discussions of AA for drought hazards proport a need to work with 'dynamic vulnerabilities'. Boult et al. (2022, p.5) propose a 'hybrid framework' as one way of overcoming limitations in capacities to assess dynamic and uncertain futures by *"building on a predefined system and incorporating real-time judgement of dynamic vulnerability"* to account for multi-hazard interactions. For GLOFs this could mean having a baseline 'most-likely' model (if one could be scientifically-determined) or even working with the assumed 'worst-credible case' (as some assessments have modelled), adjusting as the disaster unfolds to account for unanticipated vulnerabilities or complex intersecting hazards (see section 5.5.1). Associated preparedness activities could help in dealing with such uncertainty, ensuring system functionality under multiple future scenarios (McConnel and Drennan, 2006; Coppola, 2011); it is, however, noted this approach may not shape the most effective responses to specific contingencies.

The importance of forecast accuracy

This section summarises the interview insights gained in relation to issues of forecast accuracy, a common theme arising across discussions with AA actors.

Each hazard type appears to have different levels of confidence and detail to which it can be predicted. Interview respondent 02 discusses their organisation's experience using indicators to assess the flood potential of different rivers. They reflect upon times indicators suggested rivers should have crossed their predefined ‘red level’, yet no impacts were observed in the field. Other respondents communicate similar misinforming alerts. Lakes have similarly previously been ‘forecast’ as potentially dangerous, and subsequently removed from PDGL classifications without GLOF occurrence (e.g. Bajrachara et al., 2020a). This indicates a recognised potential for inaccurate long-term GLOF forecasts, with implications for implemented forecast-based actions in the form of ‘wasted’ resources or misguided risk communication.

> *“They set some kind of raw threshold … and accordingly they just act. Anticipatory action here is not always that robust, because there is a chance you will be triggering in areas when the landslide is not occurring, and there could be landslides where you have not anticipated.”* (R5)

A strong relation was made to secure forecasts (e.g. weather signals) being foundational to AA, with observed pessimism among some respondents regarding capacities to implement effective early actions in the face of uncertain forecasts:

> *“Limitations in technical abilities to create forecasts compromise capacities to design effective anticipatory actions.”* (R2)

> *“We cannot make anticipatory action happen with the existing uncertainties in the forecast.”* (R6)

Strengthened hazard forecasting systems are thus suggested to stand as a prerequisite for effective AA. The criticality of reliable forecasting data and predictions is reaffirmed in wider discussions on AA regarding flash floods in Bangladesh (Sheikh, 2022) and Nepal’s national dialogue on AA (NDRRMA, 2022). Start Fund (2022) suggest robust forecasts require greater integration of non-humanitarian actors’ expertise. Their FOREWARN works to enhance the systematic integration of actors with hazard forecasting and analysis capacities to support humanitarians in predicting imminent disaster impacts.

> *“Normally when we set up the anticipatory action system, we try to use the best possible forecast, those that are more reliable.”* (R5)

Discussions around the level of trust in expert assessments varied, with relatively high confidence noted by respondent 01 (“*if they say it’s safer then we don’t need to do more detailed assessments in those areas*”) for preliminary landslide risk assessments. NDRRMA (2022), however, question whose forecast can be considered reliable to act in anticipation and thus where expenditures should be made. Respondent 05 reiterated this sentiment suggesting predicted events are not always viewed as secure means to invest. Another similarly noted the “*hesitation of the government to agree to certain anticipatory and early actions”* (R2). These concerns are collectively proposed to underline the importance of co-designing elements across the IbF process, from hazard assessments to applications in early action design, to ensure trust in forecasts and ultimately investment in AA.

Some AA actors indicated a lack of confidence that advances in hazard modelling will perfect capacities to accurately forecast disaster events:

> *“Even when you work with multiple indicators and develop some kind of model, still I doubt this will work effectively in every instance.”* (R5)

This respondent went on to question the 'robustness' of AA where triggering mechanisms are either prone to 'false alarms' (no hazard is realised) or fail to cross established thresholds for action prior to hazard events. This is noted as a particular concern for landslides given the multiple (intersecting and uncertain) indicators used in developing forecasts. The general acceptance of imperfect forecasting capacities among respondents was aligned with suggestions that actors must simply understand the limitations of the data they are working with. Respondent 05, for instance, suggests working with 'false alarm ratios' to prepare for such scenarios.

Acceptance among actors of a lack of robustness in prediction capacities is partly assigned to the fact this is a *"new concept in Nepal"* (R4) and learnings will be gained from applications of IbF. This study's respondents appear to view IbF as an incremental learning process, improved through piloting and simulation exercises.

> *"Maybe they don't get it right every time* [but] *as we get more understanding, more knowledge on all those things … we get more experience developing different indicators of landslide prediction."* (R4)

Although experiencing hazard events is one method of learning, developing scenarios, improving risk modelling capacities, and undertaking scientific assessments of (previous) hazard trigger mechanisms could all contribute to enhanced forecasting capacities. This is especially relevant for more 'one-off' events like GLOFs. Insights into AA for more recurrent hazard types suggests a utilisation of past events to validate models and improve IbF capacities. While this is possible to an extent for GLOFs, the lack of reconstructed event data appears a key limitation to testing model accuracy. A major constraint in on-site model validation also lies in the fact that most GLOFs are non-recurrent events (Shrestha et al., 2021). The ability to utilise past GLOFs to inform IbF in the way it is for more recurrent hazard types (e.g. monsoon floods) is thus restricted.

How certain forecasts need to be to invite investment appears to be highly situational and dependent on funding requirements. This could be significant for determining the willingness to act on GLOF forecasts, especially given the observed state of risk data for Nepal's PDGLs, with limited confidence in forecasts and discrepancies among risk assessments. Interview respondent 02, however, stressed Nepal is in a good position to work with IbF because "*the national DRM policy, strategic plan of action, and documents at provincial and local level all emphasise a need for better preparedness*". Respondent 01 similarly recognised "*a momentum on early action*" in Nepal. The gradual increase in forecast-based funds should also create greater incentive to process complex risk data and use this to act in advance of anticipated events (Coughlan de Perez et al., 2016).

GLOF model capacities

Given the observed importance of clarifying forecasting capabilities, capacities to anticipate the impacts associated with forecast GLOF scenarios are assessed here using the outputs of the literature review.

Several of the risk assessments studied explicitly recognise GLOFs could occur in several ways other than their modelled scenario(s) (e.g. Sattar et al., 2021), reflecting the general observation that understandings of potential future GLOF dynamics remain uncertain for most PDGLs (Taylor et al., 2023).

One thing particularly lacking within the assessed studies is a multi-hazard perspective for downstream cascading hazards. While some include riverbank erosion, undercutting, and destabilisation processes in their assessment of ‘at-risk’ settlements beyond the immediate modelled inundation zone (e.g. Khanal et al., 2015a; Allen et al., 2022), insights from past events demonstrate a need for widespread secondary hazard zone mapping in GLOF models to avoid underestimating potential impacts (Kropáček et al., 2015; Sattar et al., 2022). Chen et al. (2017) note the threat of landslides and debris flows cascading from GLOF events in the Koshi basin, pointing to the landslides induced by the 1981 transboundary Zhangzangbo GLOF at Nyalam. The importance of modelling multiple possible modes of flow evolution is further illustrated by Maskey et al. (2020) in their recognition of the potential for transported debris blocking river channels and creating new hazards downstream (i.e. 2017 Langmale flood). Floodwaters may also cascade further downstream than existing models extend. To account for such complexities and accurately project impacts, outburst models require more advanced techniques and data acquisition (Schneider et al., 2014; Kropáček et al., 2015; Sattar et al., 2022). Clague and O’Connor (2021) reassert the idea that recent advances in GLOF impact prediction have been enabled by anticipating process cascades through the coupling of multiple physically-based models. Process cascades are common in mountain environments with glacier lakes seen as ‘multipliers’ of the damage potential of certain hazard events (Haeberli and Whiteman, 2021). The analysis of GLOF risk assessments thus points to a need for more physically-based models since only four (of 47) PDGLs have these in place.

It is dangerous to assume the smaller of the classified lakes pose less of a threat, considering observed outbursts like that of Gongbatongsha caused severe destruction relative to the small volume of water released following debris entrainment and its transformation into a debris flow (Sattar et al., 2022). The lack of GLOF inundation models across Nepal’s PDGLs is thus a point of concern for complete risk knowledge to enable accurate forecasting of GLOF events since lake size not necessarily comparable to the risk posed. There is a risk in restricting assessments solely to lakes fulfilling this susceptibility criterion without consideration of potential emergent scenarios.

Limitations in GLOF model capacities can be partly put down to a lack of in-field surveys of PDGLs to enable accurate estimations of debris, ice, and water volumes in projected outburst scenarios (ICIMOD, 2021; Sattar et al., 2021), with geophysical mapping of moraines also noted to improve outburst simulations (Shrestha et al., 2010). Studies depending on remotely-sensed data are thus liable to influential inaccuracies in discharge estimations. However, accurate modelling of outburst transformations into debris flow is, even in the presence of field surveys, noted to host uncertainties given the limited observations of past flow dynamics (Clague and O’Connor, 2021).

Uncertainties and discrepancies in modelled outputs overall appear to arise from neglected input parameters, low spatial resolutions, a lack of field data, and deficient understandings of breach mechanisms. Inconsistencies between assessments are of significance to IbF capacities since they appear to substantially change projected impacts downstream (e.g. the number of inundated settlements), as well as flood arrival times. A present lack in capacity of models to accurately anticipate GLOF impacts is overall suggested to be likely in the presence of incomplete, non-physically-based, non-multi-hazard models which do not consider a representative range of possible future scenarios.

Working with (multiple) scenarios

Following the above discussion, it is assumed a single predictive GLOF model would unlikely perfectly represent the future scenario that ultimately emerges. This is a result of the numerous intersecting and influential parameters involved in predicting outburst magnitudes and mechanisms (e.g. non-homogeneous moraine materials, complex processes of breach development; Clague and O'Connor, 2021). Even if an approach were to focus on a 'most-probable scenario', acknowledging the potential for the emergence of alternative scenarios could be key to enabling fully 'risk-informed' preparedness for GLOFs. This is exemplified by respondent 03's experience in past GLOF response and preparedness operations in Pakistan:

> *"In the initial assessment, we anticipated the flood will come and will damage the area on the way and join the main river. But, instead of draining it, the flood came and blocked the river and one of the lower villages was submerged. That was not in our planning."* (R3)

> *"We were planning on that side and then we had heavy rain, and the flood came from another valley."* (R3)

This respondent highlights the ultimate failings in working with misguided hazard assessments. They suggest even though they developed four scenarios, another (unaccounted for) scenario emerged, nullifying efforts to anticipate and mitigate risks in the project area. These experiences appear to motivate a desire to uphold a state of preparedness for multiple possible futures in relation to anticipated GLOF events. Existing risk data on GLOF threats in Nepal may thus be insufficient for holistic IbF since most studies assessed consider only a few possible scenarios. Maskey et al.'s (2020) study of Lower Barun and Thulagi models the 'most-likely' 20m breach scenario of four possible breach heights considered. To work effectively with IbF, it could be helpful to expand such models to encompass a broader range of possible futures to enable an adequate assessment of potential impacts.

Assessing various scenarios via a range of modelling approaches could be one way of improving known uncertainties in IbF to effectively inform DRM strategies. Yet, it is noted by some interview respondents that working with too many scenarios in AA could be overwhelming and impractical for DRM actors. Models would thus ideally enable the assessment of a manageable but reflective range of possible futures. Working with multiple scenarios with inconsistent specificities in projected impacts (e.g. numbers displaced) could also pose a challenge for developing EAPs. This creates a demand for developing capacities to work across multi-contingency plans, with EAPs adapted to situations with differing humanitarian needs or resource requirements (Botez, 2010; WMO, 2017). Retaining flexibility in EAPs could further enhance capacities to account for a range of potential forecast hazard contingencies and override misinformed assumptions in anticipated impacts (Perry and Lindell, 2003; Choularton, 2007). Capacities to build and work with scenarios should be developed during the proposed readiness phase. The proposed framework creates the potential to refine EAs based off observed triggers indicating the emergence of a particular (set of) scenario(s), improving capacities to work with complex risk data.

Scenarios are noted to be ‘highly effective tools’ in DRM decision making, providing a structured means of planning and platform to anticipate associated impacts (Strong et al., 2020). To address uncertainties in IbF and develop ‘robust strategies’, strategies should satisfy the objective of mitigating impacts under multiple anticipated scenarios (ibid.).

5.4.3 Developing early action protocols

Stage 3 of the readiness phase relates to the development of capacities to implement early actions, with the discussion here broadly revolving around developing thresholds for early action and local-level capacities to implement early actions. Associated activities should be aligned with the forecast impacts.

“The municipality and community define their early actions.” (R4)

Although some early actions are suggested throughout this paper, insights from interviews suggest applications should be highly contextually-grounded, shaped by at-risk populations. This will ensure anticipated impacts are reflective of community needs. Studies, like that of Khanal et al. (2015a) could, following this reasoning, be expanded across areas downstream of identified PDGLs to develop locally-influenced forecasts through focus-group discussions.

Shifting the temporality of decision making

Interview respondents suggest the time available to operationalise actions will be increased if impact assessments are conducted, and EAPs designed, in advance of established activation triggers. Having protocols aligned with pre-defined triggers will thus increase response efficiency by shifting decision-making processes well in advance of any given hazard event (Suarez and Tall, 2010). The short lead times associated with GLOFs suggest IbF and pre-planned early actions serve as an appropriate approach to DRM for this hazard type.

Working in anticipation of a crisis also enables better preparedness for effective response by understanding pre-existing community coping strategies (UNOCHA and Start Network, 2022). By anticipating needs through IbF, associated preparedness activities can involve inclusive processes (e.g.) in shaping the design of evacuation sites. NDRRMA (2022) reaffirm early action design should involve inclusive, participatory impact assessments to prioritise community-identified needs. This could also help in developing approaches that fit “*within the social structure of at-risk communities*” as purported by Thompson et al. (2020, p.7). Local capacities and desires are thus key considerations in defining the potential solution space, with their inclusion enabled by increasing the time available to plan operations.

“Most of the [evacuation] *sites are closely discussed with the community.”* (R1)

“Communities act because they jointly do the surveys.” (R3)

Working through a ‘participatory approach’ in the design of early actions and operating closely with local disaster management committees (LDMCs) is indicated by some interview respondents to help overcome barriers to the adoption of certain proposed early actions. Having constant conversations with the community asking “*why wouldn’t they move*” in the face of a warning message, with actionable responses to address such as “*there’s no drinking water*”, “*sanitary conditions*”, or “*privacy*” (R1). Creating an enabling environment is suggested to be key to the adoption of early actions (UNOCHA and Start Network, 2022).

Strengthening community-level response capacities

Developing capacities at the local level to respond to anticipated GLOF events will likely be key to mitigating associated impacts. The relatively isolated nature of mountain communities places particular emphasis on the importance of developing local capacities for DRM; especially since disaster management committees may be spatially distant from at-risk communities and unable to provide critical response activities in the immediate aftermath of a GLOF (e.g. Solokhumbu district headquarters and Imja Tsho; UNDP, 2013). Local institutions exist in mountainous Nepal (Thompson et al., 2020), but in the assessed absence of complete risk understandings, their capacity to effectively respond to GLOF events is assumed inadequate in many at-risk valleys.

An actor working with landslide IbF stated:

> “[We need] *functional local emergency operation centres or systems in place that warrant that the community receive and understand the information and there is immediate relief and response. Not having that functional structure at the palika level, at the local level, I think that keeps us away from the opportunity to implement early actions.”* (R1)

This summarises the general sentiment among respondents of the importance of developing capacities within a highly localised system when working with AA. Although national DRM guidelines exist and address the division of local-level responsibilities, NDRRMA (2022) recognise economic vulnerabilities at the local-level often lead to non-disaster-oriented priorities. Respondent 01 second this idea through their discussion of at-risk persons not evacuating despite early warnings, prioritising their livelihood assets. Since adapting to environmental hazards is not always a priority of mountain communities (Hewitt and Mehta, 2012), more resources should be invested into responsible local bodies, as high-level policy commitments are futile if their implementation is unachievable (Scott and Salamanca, 2020).

The need to develop local forecasting capacities was also stressed (Respondent 02). Chen et al.’s (2021) web tool for Tsho Rolpa is one example of how capacities among LDMCs could be enhanced to assess risks and utilise longer-term IbF to inform preparedness. The observed lack of sustainability of previous GLOF EWSs in the Nepal Himalaya (Clague and O’Connor, 2021) combined with the negative outlook of interview respondents on the capacity of local emergency operation centres to operate monitoring equipment (primarily due to deficient human resources) suggest a need for prioritisation of local capacity development and investment. A lack of such capacities is a noted point of concern for enabling the application of IbF as proposed here.

> *“At the ground level, it will be the communities who take the first actions. They understand they are the first responders.”* (R1)

This quote reiterates the importance of developing local-level DRM capacities. This actor particularly stressed the importance of developing capacities to implement early actions within LDMCs, including trainings on risk mapping, utilising trigger signals, and preparing for effective evacuation. It is important for implementing actors working in the space to integrate and develop the capacities of local government, with the cocreation of knowledge and knowledge-gap identification seemingly key to effective applications of AA in Nepal.

> *"It makes sense to share the rainfall forecast information and anticipated impacts so communities can take better decisions on what to do during the monsoon and how to plan their activities. Also, for local government to allocate resources and interventions accordingly."* (R1)

It is taken from responses like these that developing the capacities of exposed populations to make informed judgements on risk data will involve both transparent communication of this data as well as training in its evaluation to act on emerging (and potentially unforeseen) contingencies. This is especially pertinent given Thompson et al.'s (2020) observation that GLOF risk knowledge is not systematically transferred to isolated mountain communities and remains within external institutions. Inclusive IbF processes could ensure ownership over risk knowledge and enhance capacities for exposed populations to undertake their own informed AA, proactively mitigating risks. Strong et al. (2020) additionally proport that engaging communities in forecasting scenarios will be more effective than communicating 'technical' risk data. The combination of enhanced risk knowledge and empowerment to adopt early actions (e.g. educating on safe evacuation routes, accounting for mobility constraints) will be key to the effective translation of IbF into risk-reducing actions.

Fitting into existing systems

It appears common for organisations working with AA in Nepal to work with and through local governments, with attempts to shift focus from primarily response-oriented modes of governance.

> *"At the implementation level, at the local level, the whole governance is still around response."* (R1)

It is suggested by some actors that if processes could be linked to existing systems and processes, they would be more easily accepted and understood by different actors, including local governments. Thus, to enable AA, it is implied any new activities, resources, and investments should be generated within existing governance systems. Building on pre-existing systems and local capacities was a noted point of focus across practitioners, with respondent 01 suggesting their organisation work with the Department of Hydrology and Meteorology's existing risk information sharing capacities and relations with local governments. While apparent for governance systems, similar connotations were drawn for building upon, rather than around, existing community structures and processes.

> *"The community themselves have a plan … they have a location where they usually assemble … we don't force the people to change what they do."* (R1)

Arising from several sources was the idea of drawing upon communities' 'standard positive coping strategies' in early action design (e.g. UNOCHA and Start Network, 2022; Start

Fund, 2022). Respondent 01's organisation assesses "*whether where people normally move is actually safe*", then integrate these as their suggested sites for evacuation. Supporting processes include identifying the best possible routes from each in the community to those sites.

While more pertinent for recurrent hazard types, since non-recurrent GLOF threats are less likely to be aligned with experience-driven coping behaviours, the overall idea still stands that community capacities are not something to be built from scratch. EAP design processes for GLOFs should thus be collaborative processes. An interesting example of a possible point upon which to build capacities stems from the most recent recorded GLOF in Nepal, the outburst of Pemdang Pokhari and associated Melamchi disaster (Maharjan et al., 2021). Here, informal early warning and response networks were established among downstream communities mitigating humanitarian impacts (ibid.). Formalising such emergent systems by working under an anticipatory lens (i.e. disseminating contextualised IbF) could be beneficial for upstream communities and ensure the inclusion of vulnerable households.

Thresholds for early action

The idea of having 'pre-agreed thresholds' is that these can trigger the activation of certain actions or EAPs to enhance the efficiency of response to an anticipated threat. Using the insights from the prior discussed GLOF triggers, thresholds for initiating actions (e.g. evacuation) in anticipation of an imminent threat could relate to high-certainty (A2) trigger types such as mass movement into a lake, a specified drop in lake level, or a fixed seepage discharge through the moraine dam. Lower-certainty (A1) thresholds could be established and involve monitoring precursory indicators of neighbouring slope failure through satellite data or seismic monitoring networks (Allen et al., 2022), creating the potential for activating short-term forecasts for specific lakes in advance of outburst. However, Allen et al. (2022, p.3780) reaffirm such "*real-time operational monitoring systems are rare and remain an important research priority*", posing a limitation to developing any operable thresholds without advancing monitoring capacities.

Thresholds for early action can be aligned with a single (or set of) indicator(s) (e.g. Asia-Pacific TWGAA, 2023). Looking at past GLOF events, the 2013 outburst of Chorabari lake (Indian Himalaya) demonstrates the importance of accounting for intersecting triggers (monsoon-rain/avalanching/snowmelt) (Rounce et al., 2016), yet the possibility of such a complex event does not appear to be represented in any modelled GLOF assessed here. The ability to determine thresholds that account for possible intersecting GLOF triggers is thus uncertain.

The issue of setting thresholds indicating the likely emergence of a hazard event was noted when working with landslide forecasting data, where model complexity and the intersection of multiple triggering parameters created issues for determining specific triggers that enable short-term prediction. The insights gained from practitioners working with landslide forecast-based early actions regarding prediction capabilities were thus helpful for informing the framework for GLOFs since, similarly, their "*prediction is not always* *straightforward*". In the same sense hazard forecasters face challenges pre-empting the exact moment and point at which land will slip, precise predictive capacities for GLOFs presently appear largely limited to the point at which the outburst occurs. However, unlike landslides. there is a defined lead time for life-saving early actions post-hazard onset in the case of GLOFs, enabling the point of outburst to be utilised as a threshold for action.

For some hazard types, thresholds are designed not only around hazard parameters, but also the coping capacities of exposed communities (e.g. Gettliffe, 2022). It is, however, presently unclear how this type of threshold could be aligned with sudden-onset hazard types, with present applications identified only for drought-related risks.

> *"That's what anticipatory action really wants to do …* [see] *how we work with the prediction, how we allocate the resources well enough before so that we could really implement action in time."* (R5)

The idea that working with thresholds enhances response efficiency was noted by multiple respondents. A common understanding among involved agencies and stakeholders of the actions aligned with a given threshold alert was suggested to facilitate this efficiency.

> *"When we design the protocol, the roles of different sectors are mentioned, and it is agreed before what could be done once there is a forecast."* (R1)

> "[It is] *already agreed which agency will do what actions, so maybe, agency one provides the cash, another provides the agreed non-food items, then other agencies go with agreed services like psychosocial counselling or send women health volunteers at the community level."* (R2)

Cluster preparedness (for AA)

Discussions with practitioners in Nepal revealed a tendency for a cluster-oriented DRM approach, more systematically at higher governance levels but also trickling down to LDMCs. The observed tendency for emerging AA activities to conform with existing systems could suggest a cluster approach is pertinent to framing the discussion of an IbF system for GLOF risk management in Nepal. IbF could be used to predefine cluster-specific responsibilities within EAPs to ensure all anticipated needs are adequately targeted in the face of a GLOF event. Co-developed by the NDRRMA, DHM, and the local government authorities for *"five high-risk municipalities along the Karnali and Babai River basins"* (NRCS et al., 2021, p.5), EAPs were noted to aid coordination and responsibilisation, with the ultimate effect of mitigating disaster impacts.

5.5 The Activation Phase

This section discusses the proposed activation phase, covering insights on actors' willingness to undertake low-regret AA 'in vain'. As previously suggested, IbF for GLOFs should be grounded in the context of application, as such, any suggested early actions are proposed as mere guidance informed by the context of this study's inquiry.

5.5.1 Refining IbF scenarios

This component of the framework enables the addition of dynamic risk information to refine short-term forecasts in line with the emergence of (predefined) triggers indicating enhanced outburst likelihood. By narrowing the likely range of anticipated scenarios, early actions could be implemented with greater precision and certainty in the forecast. To extend the time for application of early actions, the bulk of scenario analysis should be conducted in advance of activation triggers (section 5.4.3). However, this stage creates space for adjusting forecasts in line with emergent risk data, with observed triggers indicating the emergence of a defined (set of) scenario(s).

One approach that could be applied in this stage to overcome forecast uncertainties and account for dynamic risks is to work with 'soft triggers' (Asia-Pacific TWGAA, 2023). These combine predefined thresholds for action with additional decision-making processes before implementing AA to account for additional risk information and uncertainties in predictions. It is stressed that discretionary trigger elements should involve clear protocols to avoid decision-making delays that reduce the time available to act. Linking clear actions to forecasts can negate a lack of clarity in decision-making (Coughlan de Perez et al., 2016).

5.5.2 Implementing EAPs

This stage comprises the main component of the activation phase - the implementation of pre-defined early actions upon fulfilment of the aligned activation thresholds.

Willingness to undertake anticipatory actions "in vain"

There appears a willingness among interviewees piloting AA to act even where it is not certain forecast impacts will manifest. Discussions of this type of action were commonly aligned with ideas of purporting 'no-' or 'low-regret' solutions (e.g. in the form of forecast-based financing). UNOCHA (n.d.) similarly stress the need for 'no-regret' anticipatory actions, with no negative consequences arising from proposed behaviours in the face of mis-assessments of risk. Given the conflicts across GLOF models in this study and deficiency of 'high-certainty' forecasts, a low-regret approach to anticipatory and preparedness actions would likely be appropriate for this hazard type.

> *"Weather science is very weak in our country, so implementing anticipatory actions with full confidence is challenging."* (R2)

Acting 'in vain' in the context of GLOFs is primarily correlated here with the proposed actions aligned with the lower-certainty readiness triggers, rather than A2 triggers indicating certain hazard occurrence. Actions like evacuating all households lying in the modelled 'worst-case' inundation zone could, however, also be described as acting in vain if this scenario does not ultimately emerge. Here, discussions with the community could be important to outline willingness to adopt anticipatory actions related to levels of perceived risk acceptance and model confidence.

'Low-regret' solutions

One respondent (R5) described low-regret actions as "*building the resilience of communities while not creating a lot of issues*". This type of action was noted to be effective when working with forecasts that are ultimately false alarms. Coughlan de Perez et al. (2016) similarly remark that AA taken in vain can nonetheless strengthen community resilience but note the destroyed potential for the alternate use of resources for other humanitarian needs (in the case of stressed funds) had there not been a false-positive trigger. So, determining what can be classified as a 'low-regret' activity will likely depend on the values accounted for.

Gettliffe (2022) discuss a 2-tier model for AA (alike this study's) for dry-spells in Malawi. The first trigger-type they label a 'predictive no-regrets trigger' (reflective of the readiness trigger proposed here) which activates 'no-regret' protection and WaSH activities. Some commonly applied actions extracted from Anticipation Hub's 'Early Action Database' deemed relevant to both anticipation phases include (un)conditional cash distribution, asset storage, disseminating risk information and early warnings, evacuation, and pre-positioned shelter kits. One respondent (R1) illustrates how evacuation cannot always be classified as a low-regret solution by stressing the implications for livelihoods and wellbeing. This emphasises the importance, once again, of considering the accuracy of forecasts when designing EAPs, and is why only higher-certainty activation triggers are proposed to initiate evacuation procedures here.

Evacuating exposed populations

Evacuation is likely to be the most appropriate early action following an A2 trigger given the anticipated operable lead time for many populations downstream of PDGLs.

Evacuation was a commonly discussed early action among respondents with a common associated preparedness activity being the pre-identification of evacuation sites. One respondent (R2) particularly stressed an area for improvement in Nepal being accelerating activities relating to the identification and protection of open spaces, evacuation routes, and critical infrastructure. The models in this study mapping inundation limits for different scenarios (e.g. Sattar et al., 2021) could enable risk-informed evacuation (e.g. in the form of route planning). However, the limits in models and IbF capacities, could be misleading for informing such plans. Posch et al. (2019), for instance, suggest that while GLOF evacuation centres have been identified and mapped for Imja, the lack of a multi-hazard perspective means "*some centres are located in high geomorphic hazard areas*". (Multi-)hazard models are thus suggested to be key to informing the availability and accessibility of safe spaces for evacuation and ensuring no further risk to displaced communities.

Deficient anticipation of and planning for shelter locations, conditions, and services can create further risks for vulnerable disaster-displaced populations (IFRC, 2017). It is suggested that holistic IbF for GLOFs could ensure the adequate and appropriate pre-positioning of resources in evacuation locations by assessing the projected number of displaced persons and their needs, as well as (pre-)identifying vulnerable groups.

> *"Near the site we can preposition some basic items, maybe tents or tarpaulins or water or equipment. At least near those sites you could have the basic things ready, non-food items. So once people evacuate, they have those basic supplies."* (R1)

> *"Villages were cut off, so they needed emergency food and healthcare and all sort of supplies."* (R3)

> *"We provided them some equipment … tents, rope, some food items. In areas with communities which are hazard-prone, we provide this basic support and the community keep it in a store."* (R3)

For one organisation working with landslide hazards, a geohazard assessment classified the at-risk areas and exposed households to build "*evacuation shelters, [knowing] that a lot of people in the community … are temporarily displaced*" (R1). By setting up basic facilities in the form of tents or emergency health services in 'community-based storerooms', it could be ensured people are safe for a few days, as well as developing the capacity of locals as first responders since *"many at-risk communities live in isolated areas, so the government cannot reach them initially"* (R3). IbF could thus guide (longer-term) anticipatory actions like the prepositioning of resources that are informed by forecast needs to enable the effective application of EAPs upon outburst occurrence (Weingärtner et al., 2020). Not only should this enhance local response capacities to mitigate humanitarian impacts, but also reduce response costs since pre-positioning items via road networks should be cheaper than emergency airlifted alternatives (Anticipation Hub, 2022).

Since GLOFs pose a risk to remote mountain communities, IbF could assess the exposure of transport links, like bridges, to anticipate potential limitations in capabilities to deliver humanitarian aid (RCCC, 2020). For instance, if it was anticipated roads to health centres could be blocked, related risk-reducing measures could be ensured (R3). Restricted access post-disaster to resources and infrastructure such as water sources, forests, grazing land, and schools could also be anticipated within a holistically designed IbF framework, supported by existing assessments (e.g. Khanal et al., 2015b).

6 Conclusions

This study provides a comprehensive analysis of how impact-based forecasting (IbF) and anticipatory action (AA) could be operationalised to mitigate GLOF risks associated with potentially dangerous glacier lakes (PDGLs) threatening Nepal. A systematic literature review of PDGL risk assessments enabled the assessment of capacities to anticipate GLOF threats. The research also collates insights from emerging experiences in applications of IbF and AA through six semi-structured interviews, supplemented with a non-systematic content analysis of AA and IbF documents. Both research components ultimately inform a framework showing how GLOF risks could be addressed through an anticipatory IbF approach.

The first part of the thesis analyses RQ1, exploring the state of existing GLOF risk knowledge for lakes with anticipated impacts in Nepal. Here, an overview of PDGLs and associated outburst models is presented. The findings show that of 47 identified PDGLs posing a risk to Nepal, only four are assessed to have outburst models quantifying projected impacts using physically-based hydrodynamic models. However, even where models have mapped and quantified exposed settlements, there is high uncertainty in the anticipated number of households affected in all cases, with conflicts in projected impacts and lead times across studies. Most studies additionally do not assess household-level vulnerabilities, serving as a key knowledge gap in capacities to anticipate impacts in a way that is meaningful for risk-informed activities.

The second part addresses RQ2 by introducing an IbF framework to address GLOF threats in Nepal. The proposed framework shows how IbF could facilitate the development and implementation of early actions in communities exposed to GLOF risks. The three main trigger categorisations cover both long- and short-term forecasting capacities. The design of this framework was guided by an analysis of both applications of forecast-based actions for other hazard types, as well as existing GLOF models and prediction capacities. Restricted GLOF prediction capacities, for instance, motivate the development of multiple possible scenarios within IbF to address uncertainties in complex risk data. The importance of acknowledging forecast certainty in the design of early actions was particularly apparent, with low-regret AA proposed for low-certainty forecasts.

The presented framework caters for an IbF approach that demands advanced trigger analysis and monitoring, which are advisable for enhancing GLOF prediction capacities. By assessing the risk data helpful for informing effective anticipatory risk management approaches, some areas for further research can be inferred, including in-depth assessments of site-specific GLOF prediction and hazard model capacities. The insights gained show how AA provides a systematic means to operationalising calls for advancing risk-informed disaster preparedness. Since AA is presently in its early stages of application in Nepal, discussions with actors working in other countries could further insights into the feasibility of applying AA to hazards with short lead times for action.

7 Appendix

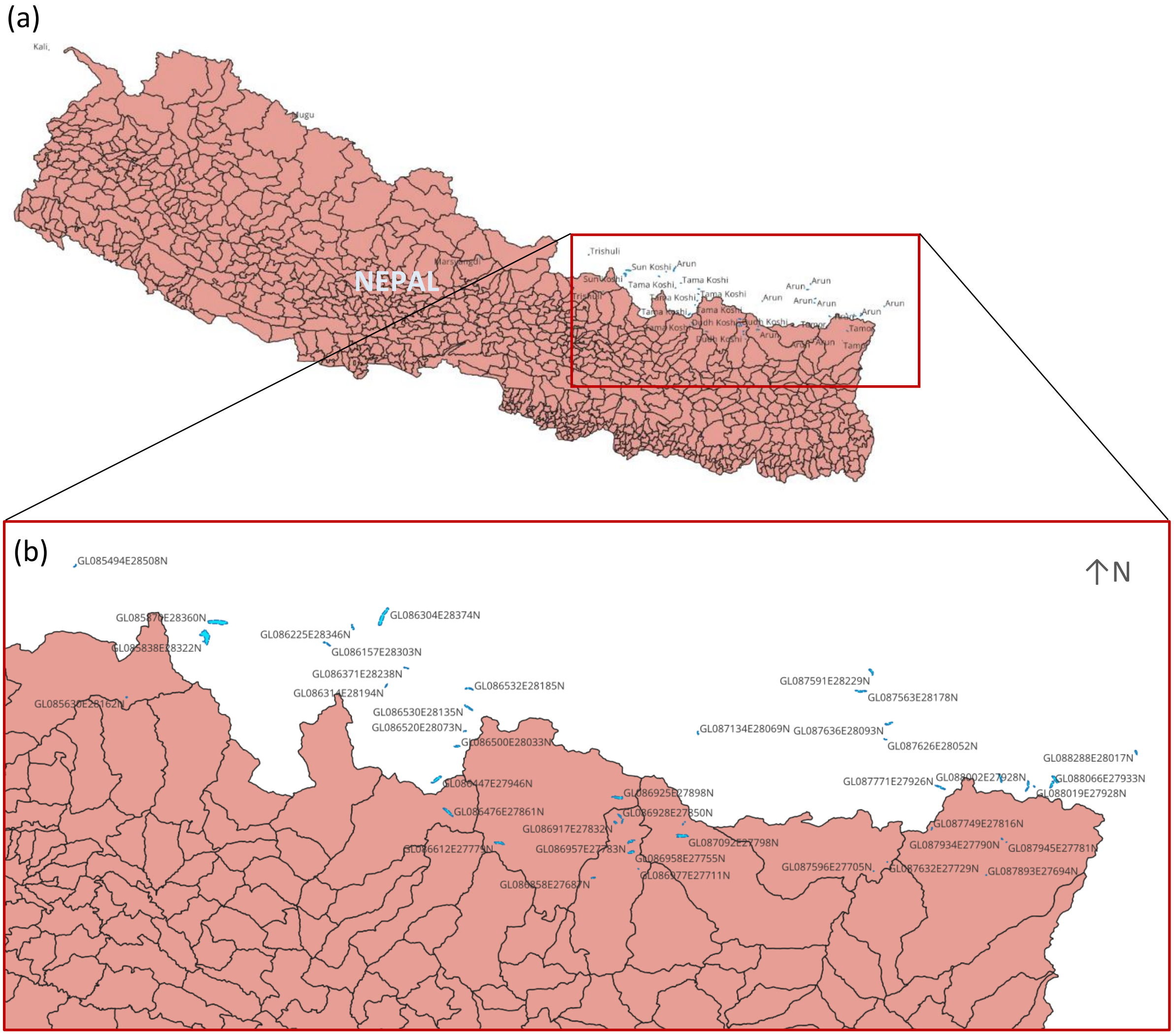
Lake ID/Name	**River basin**	**Country**	**Rank (I/II/III)**
GL087945E27781N	Tamor	Nepal	I
GL087749E27816N	Tamor	Nepal	I
GL087596E27705N	Arun	Nepal	I
GL087771E27926N	Arun	TAR	I
GL087636E28093N	Arun	TAR	I
GL087626E28052N	Arun	TAR	I
GL087930E27949N	Arun	TAR	I
GL088002E27928N	Arun	TAR	I
GL088019E27928N	Arun	TAR	I
GL088066E27933N	Arun	TAR	I
GL088075E27946N	Arun	TAR	I
GL087134E28069N	Arun	TAR	I
GL087092E27798N Lower Barun	Arun	TAR	I
GL086977E27711N	Dudh	Nepal	I
GL086957E27783N Hongu 2	Dudh	Nepal	I
GL086935E27838N Hongu1	Dudh	Nepal	I
GL086928E27850N	Dudh	Nepal	I
GL086917E27832N	Dudh	Nepal	I
GL086858E27687N	Dudh	Nepal	I
GL086925E27898N Imja Tsho	Dudh	Nepal	I
GL086612E27779N Lumding	Dudh	Nepal	I
GL086476E27861N Tsho Rolpa	Tama	Nepal	I
GL086447E27946N	Tama	China	I
GL086520E28073N	Tama	China	I
GL086532E28185N	Tama	China	I
GL086371E28238N	Tama	China	I
GL086314E28194N	Tama	China	I
GL086157E28303N	Sun	China	I
GL085630E28162N	Trishuli	Nepal	I
GL084485E28488N Thulagi	Marsyangdi	Nepal	I
GL080387E30445N	**Kali**	**India**	**I**

Lake ID/Name	**River basin**	**Country**	**Rank (I/II/III)**
GL087591E28229N	Arun	TAR	II
GL088288E28017N	Arun	TAR	II
GL086304E28374N	Arun	TAR	II
GL087095E27829N	Arun	Nepal	II
GL086958E27755N Chamlang	Dudh	Nepal	II
GL086500E28033N	Tama	TAR	II
GL086530E28135N	Tama	TAR	II
GL086225E28346N	Sun	TAR	II
GL085870E28360N Ganxico	Sun	TAR	II

GL085838E28322N Lumichimi	Sun	TAR	II
GL085494E28508N	Trishuli	TAR	II
GL082673E29802N	Mugu	Nepal	II

Lake ID/Name	**River basin**	**Country**	**Rank (I/II/III)**
GL087934E27790N	Tamor	Nepal	III
GL087893E27694N	Tamor	Nepal	III
GL087632E27729N	Arun	Nepal	III
GL087563E28178N	Arun	TAR	III

Appendix 1a. These tables display glacier lakes with their assigned danger ranking level (I/II/II) for Nepal. Outbursts with origin in Tibet in the table are forecast to cross the border to Nepal. Data obtained from Bajracharya et al. (2020a). See Bajracharya et al. (2020a, p.30-34) for a more detailed table of PDGLs, including descriptions of specific lake features.



Appendix 1b. This figure shows an outline of Nepal and its administrative boundaries (obtained from link). PDGL data was obtained from Bajrachara et al. (2020b) and downloaded into QGIS (2023) software. The PDGLs are labelled by sub-basin (a) and glacier lake ID (b). The zoom-in depicts the eastern part of Nepal where the majority of GLOF risk as presented by Bajrachara et al. (2020a,b) is suggested to be concentrated. The westernmost lake lies in India, while the rest mapped outside Nepal's coloured bounds lie in Tibet.

Lake name	Date of GLOF	Recorded impacts	Related literature
Tiptola (Olangchun Gola 1)	1963	- 4 lives lost - 3 livestock affected - 50 residencies damaged - Cropland destroyed	Byers et al. (2020)
Nagma Pokhari (Phuchan)	1980	- Villages destroyed 71km downstream	Yamada and Sharma (1993); Ives et al. (2010); ICIMOD (2011); Byers et al. (2020)
Dig Tsho	1985	- 5 lives lost - 2 commercial buildings destroyed - 30 residencies damaged - 14 bridges damaged - Nearly completed Namche Small hydro Project - Destruction of trails and bridges impacted tourist livelihoods	Vuichard and Zimmermann (1986, 1987); Ives et al. (2010); ICIMOD (2011)
Sabai Tsho / Tam Pokhari	1998	- 2 lives lost - 4 suspension and 2 wooden bridges damaged - Property and infrastructure and severely affected the livelihoods of the people living in downstream areas (Dwivedi et al., 2000)	Dwiwedi et al. (2000); Mool et al. (2001); ICIMOD (2011)
Dig Tsho	2015	- Several bridges damaged	Byers et al. (2022)
Unknown lake name (in Lhotse)	2015	- Loss of a pedestrian bridge - Loss of an outbuilding - Floodwater in the courtyard of one lodge	Rounce et al. (2017)
Langmale	2017	- Impacted downstream riverside communities in Bhojpur and Dhankuta - 50 persons total displaced (10 families) - 24 livestock affected - 80 residencies destroyed - ‘hundreds’ of infrastructure - ‘agricultural’	Byers et al. (2019)
Pemdang Pokhari	2021	- 25 lives lost - 1000 displaced (525 families) - 337 residencies destroyed - Commercial property destroyed - Public infrastructure destroyed. 13 suspension bridges, 7 motorable bridges, and road stretches. - Loss of livelihood (agricultural land; trout farmers)	Maharjan et al. (2021)

Appendix 2. Record of impact data from past GLOF events in Nepal. ICIMOD (2022) collated data on past GLOF events across the Hindu-Kush Himalaya; here, the impact data from events in Nepal, constrained between 1963-2022, have been derived to aid the analysis. ICIMOD’s excel file was sorted according to recorded impacts (e.g. residencies destroyed, residencies damaged, lives lost, displaced, etc.) and country. Transboundary events are not included here (e.g. the 2016 GLOF which originated from TAR in the Bhote Koshi River) given data constraints.

1. Would you first be able to talk me through your interpretation of the terms impact-based forecasting and anticipatory action.

- IbF: level of assessment (household, community, region, etc.); purpose?
- AA: timing; level of pre-planning

2. Which hazard types and contexts do you personally have experience working with IbF and AA?

- n/a

3. How are you (or your organisation) using IbF to inform preparedness for these hazards?

- Do you work with scenarios? How many?
- What information sources do you use to anticipate humanitarian needs?

4. Could you talk me through your experience of the process of developing forecast-based actions?

- What kinds of actors are you engaging with in the development of impact-based forecasts? … and in the design and implementation of early actions?
- VCA tasks of humanitarians and DRM authorities; hazard mapping of scientific researchers
- Do you think the types of actions being prioritised are affected by the types of actors involved the creation of IbF?
- Do you work with different humanitarian clusters for preparedness/response planning?

5. What types of impact are a priority to anticipate when designing early actions to inform adequate preparedness and operationalise forecast-based actions?

- Does impact data cover immediate humanitarian needs, or also longer-term needs concerning (e.g.) displacement or livelihoods?
- Do you work in single communities, or consider wider-reaching impacts?

6. Can you describe some of the key early action or response preparedness activities you are working on or have worked with?

- (e.g.) evacuation, FbF, raising awareness on safe shelters/open spaces/evacuation routes, pre-positioning of resources
- (if already discussed) **Are there any additional forecast-based actions you have worked with that we have not discussed?**

7. In your opinion, what are the limiting factors of IbF for informing effective preparedness?

- Have you experienced issues operationalising forecast-based actions?
- Have alternative scenarios emerged that do not align with pre-established anticipatory actions? … (if yes) What was the approach to dealing with this? … (if not) How may you approach this?

8. What level of detail is feasible when working with IbF?

- (e.g.) considering protection, gender, and inclusion (PGI); specific household-level needs
- What level of detail is useful for informing AA?

9. How important is forecast accuracy in enabling effective anticipatory or risk reducing activities?

- (i.e.) the importance of the accuracy of hazard maps for the identification of safe places and evacuation plans
- Are actions complemented by (e.g.) post-disaster needs assessments? Are actions only informed by IbF?
- How certain do forecasts need to be to be operational?

10. Do your different 'phases' of early action depend on pre-established 'triggers'?

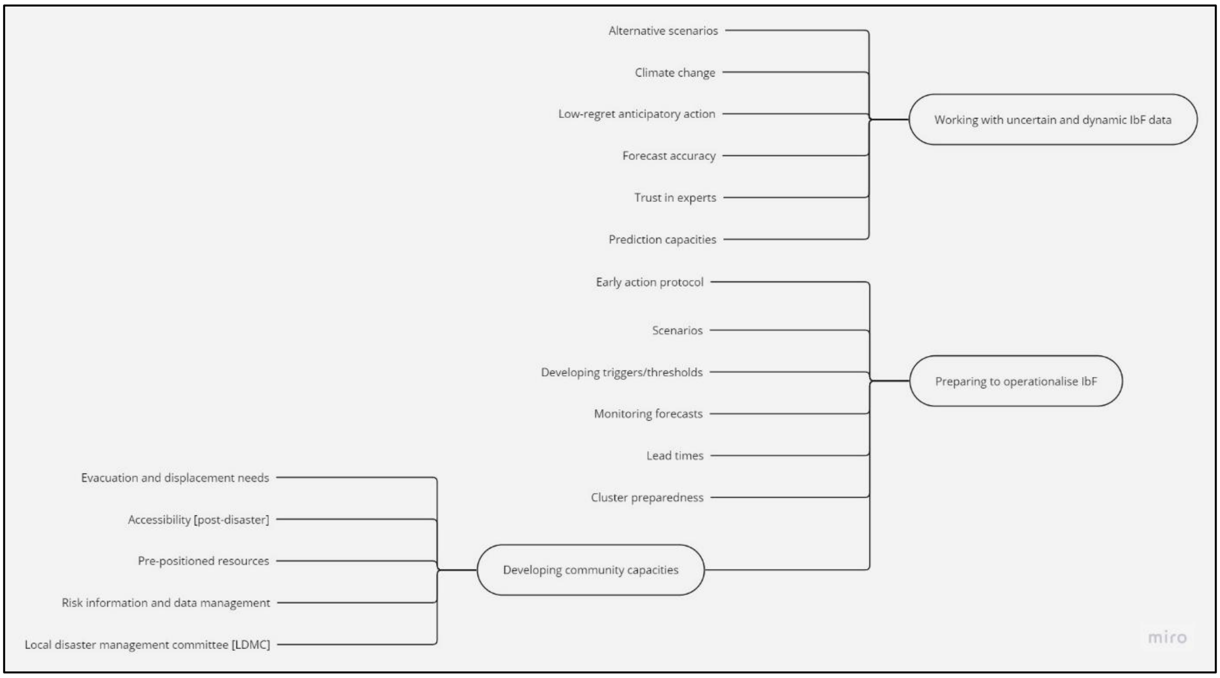
- How does this work?
- Lead times

11. How do you think working with IbF compares to more reactive post-disaster needs assessments? If you have experience with this.

- Does it affect the types of activities being implemented?

- And their effectiveness?

Appendix 3. This study's interview guide. A preliminary scoping study of IbF and AA literature informed the design of the interview guide. Bold = key question; non-bold = related prompts.



Appendix 4. This figure presents the key codes and themes extracted from the analysis of this study's interview data and shows how these codes have been categorised to inform the discussion on how impact-based forecasting could be applied to GLOF threats in Nepal.

	GLOF susceptibility parameters
Atmospheric	*Temperature*
	Precipitation
Cryospheric	*Permafrost conditions*
	Glacier retreat and downwasting
	Advancing glacier (incl. surging)
	Ice avalanche potential
	Calving potential
	Lake size
	Lake bathymetry
	Sub-, supra-, or en-glacial drainage
Dam characteristics	*Type*
	Ice-cored moraine
	Dam width to height ratio
	Freeboard to dam heigh ratio
	Lithology

	Downstream slope
	Vegetation
Catchment topography and hydrology	*Catchment area*
	Mean slope
	Drainage density
	Stream order
	Upstream lakes
Geotechnical stability	*Rock avalanche potential*
	Moraine instabilities
	Seismicity

Appendix 5. Table closely adapted from GAPHAZ's (2017) GLOF susceptibility criteria. See GAPHAZ (2017, p.57) for each parameter's relevance regarding its conditioning, triggering, or magnitude-enhancing capacities as well as associated susceptibility conditions.

8 References

Alexander, D. (2005). Towards the Development of a Standard in Emergency Planning. *Disaster Prevention and Management, 14*(2): 158–175.

Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P., and Kumari, A. (2016a). Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. *Natural Hazards, 84*, 1741–1763. https://doi.org/10.1007/s11069-016-2511-x

Allen, S.K., Rastner, P., Arora, M., Huggel, C., and Stoffel, M. (2016b). Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides, 13*, 1479-1491. https://doi.org/10.1007/s10346-015-0584-3

Allen, S. K., Zhang, G., Wang, W., Yao, T., and Bolch, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin, 64*(7), 435-445. https://doi.org/10.1016/j.scib.2019.03.011

Allen, S.K., Sattar, A., King, O., Zhang, G., Bhattacharya, A., Yao, T., and Bolch, T. (2022). Glacial lake outburst flood hazard under current and future conditions: worst-case scenarios in a transboundary Himalayan basin. *Nat. Hazards Earth Syst. Sci., 22*, 3765-3785. https://doi.org/10.5194/nhess-22-3765-2022

Anticipation Hub (2022). *Impact-Based Forecasting: Moving from what weather will be to what it will do for more effective disaster risk management.* Anticipation Hub website accessed (10.04.2023) via: https://www.anticipation-hub.org/news/impact-based-forecasting-moving-from-what-weather-will-be-to-what-it-will-do-for-more-effective-disaster-risk-management

Anticipation Hub (2023). *Anticipatory Action in 2022: A Global Overview*. Berlin: Anticipation Hub. Accessed (27.04.2023) via: https://www.anticipation-hub.org/download/file-3249

Asia-Pacific Technical Working Group on Anticipatory Action [TWGAA] (2023). Technical Standards on Anticipatory Action in Asia and the Pacific, Bangkok.

Baigal, P.M. (2021). "Threat of receding glaciers gives Pakistan communities sleepless nights." The Third Pole. Website accessed 18/02/2023: https://www.thethirdpole.net/en/climate/glofsthreat-shishper-glacier-pakistan/

Bajracharya, S.R., Mool, P.K., and Shrestha, B.R. (2007a). *Impact of Climate Change on Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan.* International Centre for Integrated Mountain Development (ICIMOD), Kathmandu. https://lib.icimod.org/record/22442

Bajracharya, B., Shrestha, A.B., and Rajbhandari, L. (2007b). Glacial Lake Outburst Floods in the Sagarmatha Region. *Mountain Research and Development, 27*(4), 336-344. https://doi.org/10.1659/mrd.0783

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Sherpa, T.C., Wagle, N., and Shrestha, A.B. (2020a). *Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India.* International Centre for Integrated Mountain Development (ICIMOD); United Nations Development Programme (UNDP). http://doi:10.53055/ICIMOD.773

Bajracharya et al. (2020b). Potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India. Kathmandu, Nepal: ICIMOD. [Published data]. Retrieved from: http://rds.icimod.org/Home/DataDetail?metadataId=1971950&searchlist=True.

Blaikie, N. (2010). *Designing Social Research: The Logic of Anticipation.* (2nd Ed.) Polity Press: Cambridge, UK. https://bayanbox.ir/view/1975374250584859685/Designing-Social-Research-2.pdf

Botez, R.N. (2010). *Displacement risks from glacial melting in Nepal.* The State of Environmental Migration Report. Website accessed 01-06-2022: http://labos.ulg.ac.be/hugo/wpcontent/uploads/sites/38/2017/11/The-State-of-Environmental-Migration-2010-67-76.pdf

Boult, V.L., Black, E., Abdillahi, H.S., Bailey, M., Harris, C., Kilavi, M., Kniveton, D., MacLeod, D., Mwangi, E., Otieno, G., Rees, E., Rowhani, P., Taylor, O., Todd, M.C. (2022). Towards drought impact-based forecasting in a multi-hazard context. *Climate Risk Management, 35*. https://doi.org/10.1016/j.crm.2022.100402.

Byers, A.C., McKinney, D.C., Somos-Valenzuela, M., Watanabe, T., and Lamsal, D. (2013). Glacial lakes *of the Hinku and Hongu valleys, Makalu Barun National Park and Buffer Zone, Nepal. Nat Hazards, 69*, 115–139. https://doi.org/10.1007/s11069-013-0689-8

Byers, A.C., Byers, E.A., McKinney, D.C., Rounce, D.R. (2017). A field-based study of impacts of the 2015 earthquake on potentially dangerous Glacial Lakes in Nepal. *Himalaya, 37*(2). Accessed (20/04/2023) via: https://digitalcommons.macalester.edu/himalaya/vol37/iss2/7

Byers, A.C., Chand, M.B., Lala, J., Shrestha, M., Byers, E.A., and Watanabe, T. (2020). Reconstructing the History of Glacial Lake Outburst Floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An Interdisciplinary Approach. *Sustainability, 12*(5407), 1-24. https://doi.org/10.3390/su12135407

Byers, A. C., Shugar, D. H., Chand, M. B., Portocarrero, C., Shrestha, M., Rounce, D. R., & Watanabe, T. (2022). Three Recent and Lesser-Known Glacier-Related Flood Mechanisms in High Mountain Environments. *Mountain Research and Development, 42*(2), A12-A22. https://doi.org/10.1659/MRD-JOURNAL-D-21-00045.1

Carey, M. (2005). Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change, 47*(2-4), 122-134. https://doi.org/10.1016/j.gloplacha.2004.10.007

Carey, M., McDowell, G., Huggel, C., Marshall, B., Moulton, H., Portocarrero, C., Provant, Z., Reynolds, J.M., Vicuña, L. (2021). Chapter 8 - A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change, (pp. 215-257) in Haeberli, W. and Whiteman, C. (2021). *Hazards and Disasters Series, Snow and Ice-Related Hazards, Risks, and Disasters* (Second Edition), Elsevier. https://doi.org/10.1016/B978-0-12-817129-5.00018-4.

Carrivick, J.L. and Tweed, F.S. (2016). A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change, 144*, pp.1-16. https://doi.org/10.1016/j.gloplacha.2016.07.001.

Central Emergency Response Fund (2021). *CERF Anticipatory Action*. https://cerf.un.org/sites/default/files/resources/211117%20CERF%20Anticipatory%20Action.pdf

CERF Advisory Group (2019). *CERF and Anticipatory Action.* Central Emergency Response Fund. https://cerf.un.org/sites/default/files/resources/CERF_and_Anticipatory%20Action_Update_June_2019.pdf

Chand, M.B. and Watanabe, T. (2019). Development of supraglacial ponds in the Everest region, Nepal, between 1989 and 2018. *Remote Sensing, 11*(9), 1058. https://doi.org/10.3390/rs11091058

Chen, N., Hu, G., Deng, W., Khanal, N.R., Zhu, Y., Han, D. (2017). Water Hazards in the Trans-boundary Kosi River Basin. In: Li, A., Deng, W., Zhao, W. (eds) *Land Cover Change and Its Eco-environmental Responses in Nepal.* Springer Geography. Springer, Singapore. https://doi.org/10.1007/978-981-10-2890-8_17

Chen, H., Liang, Q., Xiao, W. (2021a). *Buildings, infrastructure, and population in the potentially impacted areas by glacier lake outburst floods of Tsho Rolpa, Nepal, 2020*. NERC EDS Environmental Information Data Centre. (Dataset). https://doi.org/10.5285/3834d477-7a1d-4ad3-8a41-d38fc727dbd8

Chen, H.; Liang, Q.; Xiao, W. (2021b). *Outburst flood simulations of various dam failure scenarios from Tsho Rolpa glacial lake, Nepal, 2020*. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/f4292d99-de93-4a28-a821-b2a6a826df4c

Chen, H., Zhao, J., Liang, Q., Maharjan, S.B., and Joshi, S.P. (2022). Assessing the potential impact of glacial lake outburst floods on individual objects using a high-performance hydrodynamic model and open-source data. *Science of The Total Environment, 806*(3). https://doi.org/10.1016/j.scitotenv.2021.151289

Chen, N.S., Liu, M., Allen, S., Deng, M.F., Khanal, N.R., Peng, T.X., Tian, S.F., Huggel, C., Wu, K.L., Rahman, M. (2023). Small outbursts into big disasters: Earthquakes exacerbate climate-driven cascade processes of the glacial lakes failure in the Himalayas. Geomorphology, 422, 108539. https://doi.org/10.1016/j.geomorph.2022.108539

Choularton, R. (2007). *Contingency Planning and Humanitarian Action: A Review of Practice*. Humanitarian Practice Network Paper (59), ODI, UK. https://odihpn.org/publication/contingency-planning-and-humanitarian-action-a-review-of-practice/

Clague, J.J., and O'Connor, J.E. (2021). Chapter 14 - Glacier-related outburst floods. (pp. 467-499) in: *Snow and Ice-Related Hazards, Risks, and Disasters*. Elsevier. https://doi.org/10.1016/B978-0-12-817129-5.00019-6

Coppola, D.P. (2011). *Introduction to International Disaster Management* (2nd edition). Oxford: Butterworth-Heinemann (Elsevier).

Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Amuron, I., Bamanya, D., Hauser, T., Jongma, B., Lopez, A., Mason, S., Mendler de Suarez, J., Pappenberger, F., Rueth, A., Stephens, E., Suarez, P., Wagemaker, J., and Zsoter, E.: Action-based flood forecasting for triggering humanitarian action, *Hydrology and Earth Systems Science, 20*, 3549–3560, https://doi.org/10.5194/hess-20-3549-2016.

Creswell, J.W. (2013). *Qualitative Inquiry and Research Design: Choosing Among Five Approaches.* (3rd Ed.). SAGE Publications, Inc: California. http://www.ceil-conicet.gov.ar/wp-content/uploads/2018/04/CRESWELLQualitative-Inquary-and-Research-Design-Creswell.pdf

Cuellar, A.D. and McKinney, D.C. (2017). Decision-making methodology for risk management applied to Imja lake in Nepal. *Water, 9*(8), 591. https://www.mdpi.com/2073-4441/9/8/591

Dey, I. (1993). *Qualitative Data Analysis: A User Friendly Guide for Social Science*. London: Routledge. http://dx.doi.org/10.4324/9780203412497

Emmer, A., and Cochachin, A. (2013). The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera, and Himalayas. *AUC GEOGRAPHICA, 48*(2), 5-15.

Emmer, A., Allen, S. K., Carey, M., Frey, H., Huggel, C., Korup, O., et al. (2022). Progress and challenges in glacial lake outburst flood research (2017–2021): a research community perspective. *Natural Hazards and Earth System Sciences, 22*(9), 3041-3061. https://doi.org/10.5194/nhess-22-3041-2022

Fakhruddin, B. and Basnet, G. (2018). *Community Based Flood and Glacial Lake Outburst Risk Reduction Project (CFGORRP).* Final Report, UNDP Nepal. https://adaptationataltitude.org/sites/weadapt.org/files/aaa-portal-solutions/supporting-documents/55_te_nepal.pdf

Fecht, S. And Orlove, B. (2020). *"Seismic Monitoring May Improve Early Warnings for Glacial Lake Outburst Floods."* Climate, Earth Sciences: Press Release. Accessed via: https://news.climate.columbia.edu/2020/09/16/seismic-warnings-glacial-lake-outburst-floods/

Fischer, M., Lehnigk, K., Lützow, N., Brettin, J., Veh, G., Larsen, I.J., Korup, O., Walz, A. (2023). Himalayan hazard cascades – modern and medieval outburst floods in Pokhara, Nepal. Earth Surface Processes and Landforms, 1-17. https://doi.org/10.1002/esp.5539

GAPHAZ (2017). *Assessment of Glacier and Permafrost Hazards in Mountain Regions – Technical Guidance Document.* Prepared by Allen, S., Frey, H., Huggel, C. et al. Standing Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). Zurich, Switzerland / Lima, Peru, 72 pp.

Gettliffe, E. (2022). *'Malawi Anticipatory Action: Process Learning on Trigger Development'*. Learning report, Centre for Disaster Protection, London. https://www.disasterprotection.org/publications-centre/malawi-anticipatory-action-process-learning-on-trigger-development

Green Climate Fund (2021). *SAP022: Enhancing Multi-Hazard Early Warning System to increase resilience of Uzbekistan communities to climate change induced hazards.* Funding Proposal, UNDP Uzbekistan. https://www.greenclimate.fund/sites/default/files/document/fundingproposal-sap022.pdf

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field methods, 18*(1), 59-82.

Gurung N., Thakuri S., Chauhan R., Ghimire N.P., Ghimire M.L. (2021). Dynamics of Lower-Barun Glacier and Glacial Lake and its GLOF Susceptibility Using Geospatial Analysis and Modelling. JALAWAAYU, 1(2). https://doi.org/10.3126/jalawaayu.v1i2.41012

Haeberli, W., Schaub, Y., Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology, 293*, 405-417. https://doi.org/10.1016/j.geomorph.2016.02.009

Haeberli, W., and Whiteman, C. (2021). Chapter 1 - Snow and ice-related hazards, risks, and disasters: Facing challenges of rapid change and long-term commitments, In: Hazards and Disasters Series, Snow and Ice-Related Hazards, Risks, and Disasters (Second Edition), Elsevier, pp.1-33. https://doi.org/10.1016/B978-0-12-817129-5.00014-7.

Haritashya, U.K., Kargel, J.S., Shugar, D.H., Leonard, G.J., Strattman, K., Watson, C.S., Shean, D., Harrison, S., Mandli, K.T. and Regmi, D. (2018). Evolution and Controls of Large Glacial Lakes in the Nepal Himalaya. *Remote Sensing, 10*(5), 798; https://doi.org/10.3390/rs10050798

Hennink, M. and Kaiser, B.N. (2022). Sample sizes for saturation in qualitative research: A systematic review of empirical tests. *Social Science & Medicine, 292*. https://doi.org/10.1016/j.socscimed.2021.114523

Hewitt, K., and Liu, J. (2010). Ice-dammed lakes and outburst floods, Karakoram Himalaya: historical perspectives on emerging threats. *Physical Geography, 31*(6), 528-551.

Hewitt, K. and Mehta, M. (2012). Rethinking risk and disasters in mountain areas. *Journal of Alpine Research, 100(1)*, 1-13. https://doi.org/10.4000/rga.1653

Hultquist, C. Bucherie, A., Ayala, F., Vergara, H., Bazo, J., Wilmer, G., Navarro, M., de Sherbinin, A., Kruczkiewicz, A., and Mahoney, L. (2021). Developing a flash flood anticipatory action system for Ecuador. *AGU Fall Meeting Abstracts, 2021*. https://ui.adsabs.harvard.edu/abs/2021AGUFMGC51B..06H/abstract

ICIMOD. (n.d.). *Transboundary Working Groups: GLOFs.* ICIMOD. https://www.icimod.org/initiative/kdkh-tbwg-glofs/

ICIMOD. (2011). *Glacial lakes and glacial lake outburst floods in Nepal.* Kathmandu: ICIMOD.

ICIMOD. (2020). Potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India [Data set]. ICIMOD. https://doi.org/10.26066/RDS.1971950

ICIMOD. (2021). *Proceedings of the: Annual dialogue on the Koshi Disaster Risk Reduction Knowledge Hub*. Kathmandu: ICIMOD. Accessed via: link.

ICIMOD. (2022). *GLOF database of High Mountain Asia* [Data set]. ICIMOD. https://doi.org/10.26066/RDS.1973283

International Federation of Red Cross and Red Crescent Societies (IFRC). (2017). *Global Study: Effective law and policy on gender equality and protection from sexual and gender-based violence in disasters.* Geneva; IFRC. https://www.ifrc.org/sites/default/files/Gender-SGBV-Report_-Global-report.pdf

Iturrizaga, L. (2011). Glacier Lake Outburst Floods. (pp.381-399 in) Singh, V.P., Singh, P., Haritashya, U.K. (eds) *Encyclopedia of Snow, Ice and Glaciers.* Dordrecht: Springer Encyclopedia of Earth Sciences Series.

Ives, J.D., Shrestha, R.B., and Mool, P.K. (2010). *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment.* International Centre for Integrated Mountain Development, Kathmandu.

Karki, A., Owd, D., and Kaloga, I. (2022). *Integrating protective, gender-transformative and inclusive approaches into anticipatory action: snapshots from Nepal.* Anticipation Hub blog. Website accessed (17.04.2023) via: https://www.anticipation-hub.org/news/integrating-protective-gender-transformative-and-inclusive-approaches-into-anticipatory-action-snapshots-from-nepal

Kattelmann, R. (2003). Glacial Lake Outburst Floods in the Nepal Himalaya: A Manageable Hazard?. *Natural Hazards,* 28, 145-154. https://link.springer.com/content/pdf/10.1023/A:1021130101283.pdf?pdf=button

Khanal, N.R., Koirala, H.L., Nepal, P., Rai, D., Khanal, B., Sigdel, S., Sharma, A.R. (2009). *GLOF risk assessment of the Imja, Tsho Rolpa and Thulagi glacial lakes in Nepal.* Report submitted to International Centre for Integrated Mountain Development (ICIMOD) (unpublished report).

Khanal NR, Mool PK, Shrestha AB, Rasul G, Ghimire PK, Shrestha RB, Joshi SP. (2015a). A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from Nepal and the transboundary area. *International*

Journal of Water Resources Development, 31, 219-237. https://doi.org/10.1080/07900627.2014.994116

Khanal, N.R., Hu, J-M., Mool, P. (2015b). Glacial Lake Outburst Flood Risk in the Poiqu/Bhote Koshi/Sun Koshi River Basin in the Central Himalayas. *Mountain Research and Development, 35*(4), 351-364. https://doi.org/10.1659/MRD-JOURNAL-D-15-00009

Khadka, N., Zhang, G., and Chen, W. (2019). The state of six dangerous glacial lakes in the Nepalese Himalaya. *Terr. Atmos. Ocean. Sci., 30*(1), pp.63-72. https://doi:10.3319/TAO.2018.09.28.03

Khadka, N., Chen, X., Nie, Y., Thakuri, S., Zheng, G., & Zhang, G. (2021). Evaluation of Glacial Lake Outburst Flood Susceptibility Using Multi-Criteria Assessment Framework in Mahalangur Himalaya. *Frontiers in Earth Science, 8*. https://doi.org/10.3389/feart.2020.601288

Knox Clarke, P. (2022). *Glossary of Early Action Terms*. Risk-informed Early Action Partnership. ADAPT initiative. https://www.early-action-reap.org/glossary-early-action-terms-2022-edition

Koirala, R.R. and Saraswati, T. (2021). *Potential GLOF Impacts in High Mountains: An Example from Bhotkhola and Makalu Rural Municipality, Nepal*. AGU Fall Meeting Abstracts, 2021. Accessed (02.02.2023) via: https://ui.adsabs.harvard.edu/abs/2021AGUFMNH25A0527K.

Kropáček, J., Neckel, N., Tyrna, B., Holzer, N., Hovden, A., Gourmelen, N., Schneider, C., Buchroithner, M., and Hochschild, V. (2015). Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal, *Nat. Hazards Earth Syst. Sci., 15*, 2425-2437, https://doi.org/10.5194/nhess-15-2425-2015

Kruczkiewicz, A., McClain, S., Bell, V., Warrick, O., Bazo, J., Mason, J., Vergara, H., Horna, N. (2021). Chapter 11 - Earth Observations for Anticipatory Action: Case Studies in Hydrometeorological Hazards, (pp.237-253 in) Schumann, G.J-P. (2021). *Earth Observation for Flood Applications: Progress and Perspectives*. Elsevier. https://doi.org/10.1016/B978-0-12-819412-6.00011-0

Kvale, S., and Brinkman, S. (2009). *Interview quality. Interviews: Learning the craft of qualitative research interviewing*, 161-175.

Lala, J.M., Rounce, D.R., and McKinney, D.C. (2018). Modeling the glacial lake outburst flood process chain in the Nepal Himalaya: reassessing Imja Tsho's hazard. *Hydrol. Earth Syst. Sci., 22*, pp.3721–3737, https://doi.org/10.5194/hess-22-3721-2018.

Lamsal, D., Sawagaki, T., Watanabe T., & Byers, A.C. (2016). Assessment of glacial lake development and prospects of outburst susceptibility: Chamlang South Glacier, eastern Nepal Himalaya, *Geomatics, Natural Hazards and Risk, 7*(1), 403-423. https://doi.org/10.1080/19475705.2014.931306

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., & Allen, S. (2016). Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya-Karakoram region. *Annals of Glaciology, 57*(71), 119-130.

Lutoff, C., Creutin, J-C., Ruin, I., Borga, M. (2016). Anticipating flash-floods: Multi-scale aspects of the social response, *Journal of Hydrology, 541*(A), 626-635. https://doi.org/10.1016/j.jhydrol.2016.01.005.

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

Maharjan, S.B., Steiner, J.F., Shrestha, A.B., Maharjan, A., Nepal, S., Shrestha, M.S., Bajracharya, B., Rasul, G., Shrestha, M., Jackson, M., and Gupta, N. (2021). *The Melamchi flood disaster: Cascading hazard and the need for multihazard risk management.* International Centre for Integrated Mountain Development (ICIMOD). Kathmandu, Nepal.

Mal, S., Allen, S. K., Frey, H., Huggel, C., & Dimri, A. P. (2021). Sectorwise assessment of glacial lake outburst flood danger in the Indian Himalayan region. *Mountain Research and Development, 41*(1), R1.

McConnell, A. and Drennan, L. (2006). Mission Impossible? Planning and Preparing for Crisis. *Journal of Contingencies and Crisis Management, 14*(2): 59-70. https://doi.org/10.1111/j.1468- 5973.2006.00482.x

McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K., & Ricciardi, V. (2019). Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change?. *Global Environmental Change, 54*, 19-30.

Montier, E., Weingärtner, L., and Klassen, S. (2022). *The Potential for Anticipatory Action and Disaster Risk Finance: Guiding the setting of humanitarian targets*. ODI and Start Network Report. https://startnetwork.org/learn-change/resources/library/potentialforaaanddrf

Mool, P. K., Maskey, P. R., Koirala, A., Joshi, S. P., Wu, L., Shrestha, A. B., Eriksson, M., Gurung, B., Pokharel, B., Khanal, N. R., Panthi, S., Adhikari, T., Kayastha, R. B., Ghimire, P., Thapa, R., Shrestha, B., Shrestha, S., & Shrestha, R. B. (2011). *Glacial lakes and glacial lake outburst floods in Nepal* (pp. 1-109). Kathmandu: ICIMOD. Retrieved from https://lib.icimod.org/record/27755

Multi-Hazard Early Warning Conference III (2022). *The Third Multi-Hazard Early Warning Conference; From Stock Take to Scaling Actions on Target G: Accelerating the Knowledge and Practice of 13 Early Warning Systems for Risk Informed Resilience*. Global Platform for Disaster Risk Reduction. https://globalplatform.undrr.org/multi-hazard-early-warning-conference-iii

Nauman, C., Anderson, E., Coughlan de Perez, E., Kruczkiewicz, A., McClain, S., Markert, A., Griffin, R., and Suarez, P. (2021). Perspectives on flood forecast-based early action and opportunities for Earth observations. *Journal of Applied Remote Sensing, 15*(3), 1-17.

NDRRMA (2021). “*Interaction program between NDRRMA and provincial governments on Monsoon Preparedness and Response Plan 2021”.* BIPAD portal. Accessed 25/01/2023 via: http://www.bipad.gov.np/np/publications/detail/95

NDRRMA (2022). *National Dialogue on Anticipatory Action: Event Proceeding Report*. https://www.anticipation-hub.org/Documents/Reports/national-dialogue-on-anticipatory-action-nepal-proceeding-report-2022.pdf

Nepal Red Cross Society, Danish Red Cross, and Humanity and Inclusion (n.d.). “*Forecast-based action and shock-responsive social protection in Province 5 and Sudhur Paschim, Nepal.*” Anticipation Hub Website. Accessed (08.03.2023) via: https://www.anticipation-hub.org/experience/anticipatory-action-in-the-world/nepal/forecast-based-action-and-shock-responsive-social-protection-in-nepal

Ng, F., and Björnsson, H. (2003). On the Clague–Mathews relation for jökulhlaups. *Journal of Glaciology, 49*(165), 161-172.

Ng, F. and Liu, S. (2009). Temporal dynamics of a jökulhlaup system. *Journal of Glaciology, 55*(192), 1-15.

Nie, Y., Liu, Q., Wang, J., Zhang, Y., Sheng, Y., & Liu, S. (2018). An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis. *Geomorphology, 308*, 91-106.

NRCS, DRC, Handicap International, and RCCC. (2021). Acting in anticipation against unseasonal floods in Nepal: A Case Study on anticipatory actions taken against October 2021 floods in Karnali. Accessed via: https://www.anticipation-hub.org/Documents/Case_Studies/Case_Study-AA_against_Oct_flood-DEL-I20-66.pdf

Perry, R.W. and Lindell, M.K. (2003). Preparedness for Emergency Response: Guidelines for the Emergency Planning Process. *Disasters, 27*(4), 336-350.

QGIS (2023). *QGIS Geographic Information System.* QGIS Association. http://www.qgis.org

Posch, E., Bell, R., Fort, M., Höferl, K-M., Steiger, R. (2019). A qualitative evaluation of the glacial lake outburst flood (GLOF) risk management at Imja lake, Everest region, Nepal. *Geophysical Research Abstracts*, 21. https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,uid&db=a9h&AN=140480290&site=eds-live&scope=site.

Red Cross Red Crescent Climate Centre (RCCC) (2020). *The future of forecasts: Impact-based forecasting for early action*. https://www.forecast-based-financing.org/wp-content/uploads/2020/09/Impact-based-forecasting-guide-2020.pdf

Robbins et al. (2022). *‘Gaining user insights into the research-to-operational elements of Impact - based Forecasting (IbF) from within the SHEAR programme: Summary of Findings’.* Science for Humanitarian Emergencies and Resilience Programme.

Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C., and Watson, C. S. (2016). A new remote hazard and risk assessment framework for glacial lakes in the Nepal

Himalaya. *Hydrol. Earth Syst. Sci., 20*, 3455–3475. https://doi.org/10.5194/hess-20-3455-2016.

Rounce, D. R., Watson, C. S., & McKinney, D. C. (2017). Identification of hazard and risk for glacial lakes in the Nepal Himalaya using satellite imagery from 2000–2015. *Remote Sensing, 9*(654), 1-19. https://doi.org/10.3390/rs9070654

Rubin, H.J. and Rubin, I.S. (2012). *Qualitative Interviewing: The Art of Hearing Data*. (265pp.) SAGE Publications.

Sanjaya, G., Dhoj, J.S., and Binod, P. (2021). Overview of an early warning system for Glacial Lake outburst flood risk mitigation in Dudh-Koshi Basin, Nepal. *Sciences in Cold and Arid Regions, 13*(3): 206-219. https://doi.org/10.3724/SP.J.1226.2021.20076

Sattar, A., Haritashya, U.K., Kargel, J.S., Leonard, G.J., Shugar, D.H., & Chase, D.V. (2021). Modeling lake outburst and downstream hazard assessment of the Lower Barun Glacial Lake, Nepal Himalaya. *Journal of Hydrology, 598*, 126208.

Sattar, A., Haritashya, U.K., Kargel, J.S. et al. (2022). Transition of a small Himalayan glacier lake outburst flood to a giant transborder flood and debris flow. *Sci Rep 12*, 12421. https://doi.org/10.1038/s41598-022-16337-6

Schneider, D., Huggel, C., Cochachin, A., Guillén, S., García, J. (2014). Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Adv. Geosci. 35*, 145-155. https://doi.org/10.5194/adgeo-35-145-2014

Sheikh, K. (2022). *Flash floods in Bangladesh – and the way forward for the anticipatory action community*. Anticipation Hub Blog. Website accessed (10.03.2023) via: https://www.anticipation-hub.org/news/flash-floods-in-bangladesh-and-the-way-forward-for-the-anticipatory-action-community

Shrestha, A.B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., and Khanal, N.R. (2010). Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics, Natural Hazards and Risk, 1*(2), 157-169. https://doi.org/10.1080/19475701003668968

Shrestha, B. B., Nakagawa, H., Kawaike, K., Baba, Y., and Zhang, H. (2013). Glacial hazards in the Rolwaling Valley of Nepal and numerical flood to predict potential outburst flood from glacial lake. *Landslides, 10*, 299-313. https://doi.org/10.1007/s10346-012-0327-7

Shrestha, B.B., and Nakagawa, H. (2014). Assessment of potential outburst floods from the Tsho Rolpa glacial lake in Nepal. *Natural Hazards, 71*, 913-936. https://doi.org/10.1007/s11069-013-0940-3

Sieg, T., Kienzler, S., Rözer, V., Vogel, K., Rust, H., Bronstert, A., Kreibich, H., Merz, B., & Thieken, A. H. (2023). Toward an adequate level of detail in flood risk assessments. *Journal of Flood Risk Management, e12889,* 1-26. https://doi.org/10.1111/jfr3.12889

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333-339.

Somos-Valenzuela, M. A., McKinney, D. C., Rounce, D. R., & Byers, A. C. (2014). Changes In Imja Tsho in the Mount Everest Region of Nepal. *The Cryosphere, 8*(5), 1661-1671.

Somos-Valenzuela, M.A., McKinney, D. C., Byers, A. C., Rounce, D. R., Portocarrero, C., and Lamsal, D.: (2015). Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal, *Hydrology and Earth System Sciences, 19*, 1401–1412, https://doi.org/10.5194/hess-19-1401-2015.

Start Fund (2022). *Start Fund Impact Report 2022*. Start Network. Accessed (17.03.2023) via: https://start-network.app.box.com/s/uosrr6k0j6sakhlio01eax46c1i3komb

Strong, K., Carpenter, O., and Ralph, D. (2020). *Scenario Best Practices: Developing Scenarios for Disaster Risk Reduction.* Cambridge Centre for Risk Studies at the University of Cambridge Judge Business School and Lighthill Risk Network. https://www.jbs.cam.ac.uk/wp-content/uploads/2021/11/crs-developing-scenarios-for-disaster-risk-reduction.pdf

Suarez, P. and Tall, A. (2010). *Towards forecast-based humanitarian decisions: Climate science to get from early warning to early action.* Humanitarian Futures Programme. https://www.alnap.org/system/files/content/resource/files/main/towards-forecast-based-humanitarian-decisions.pdf

Tariq, H. (2022). *"Bridge Collapse in Pakistan Due to Glacier Lake Outburst Flood."* GlacierHub Blog. Website accessed (28/05/2022) via: https://news.climate.columbia.edu/2022/05/13/bridgecollapse-in-pakistan-due-to-glacier-lake-outburst-flood/

Taylor, C., Robinson, T.R., Dunning, S. et al. (2023). Glacial lake outburst floods threaten millions globally. *Nat. Commun., 14*, 487. https://doi.org/10.1038/s41467-023-36033-x

Thompson S.S., Kulessa B., Benn D.I., Mertes J.R. (2017). Anatomy of terminal moraine segments and implied lake stability on Ngozumpa Glacier, Nepal, from electrical resistivity tomography (ERT). *Scientific Reports, 7*, 46766. https://doi.org/10.1038/srep46766

Thompson, I., Shrestha, M., Chhetri, N., Agusdinata, D.B. (2020). An institutional analysis of glacial floods and disaster risk management in the Nepal Himalaya*. International Journal of Disaster Risk Reduction, 47*. https://doi.org/10.1016/j.ijdrr.2020.101567.

United Nations Development Programme [UNDP] (2015). *GLOF Risk Reduction through Community-based Approaches.* Accessed via: https://www.undp.org/publications/glof-risk-reduction-through-community-based-approaches

United Nations Development Programme [UNDP] (2013). *Community Based Flood and Glacier Lake Outburst Risk Reduction Project Document.* Government of Nepal, GEF, and UNDP. Accessed (12/02/2023) via: https://www.undp.org/sites/g/files/zskgke326/files/migration/np/aa21b4ccde4230b2b26dda751438572149d185892d482a1cf417b3a1737ce05a.pdf

UNOCHA (2022). *Global Humanitarian Overview 2023*. United Nations Office for the Coordination of Humanitarian Affairs. https://doi.org/10.18356/9789210024136

UNOCHA (n.d.). *How To Develop the Anticipatory Action Framework?* United Nations Office for the Coordination of Humanitarian Affairs. Website accessed (09.05.2023) via: https://anticipatory-action-toolkit.unocha.org/framework/

UNOCHA and Start Network (2022). *CERF AA Pilot Pre-Crisis Survey (PCS): Final Report*. Accessed (23/04/2023) via: https://startnetwork.org/learn-change/resources/library/pre-crisis-anticipatory-action-survey

UNDRR (2022). Strengthening Risk Analysis for Humanitarian Planning: Integrating disaster and climate risk in the Humanitarian Programme Cycle. United Nations office for Disaster Risk Reduction. https://www.undrr.org/publication/strengthening-risk-analysis-humanitarian-planning

Uprety, D. and Maden, U. (2021). *Covering all bases: Nepal's Karnali Province plans for multi-hazard early warning systems*. SERVIR-HKH: ICIMOD. http://servir.icimod.org/news/covering-all-bases-nepals-karnali-province-plans-for-multi-hazard-early-warning-systems/

Uprety, M., Sharma, R., and Bajracharya, R. (2022). *Developing an impact-based forecasting model within Nepal's national disaster information management system: the BIPAD portal.* Anticipation Hub Blog. https://www.anticipation-hub.org/news/developing-an-impact-based-forecasting-model-within-nepals-national-disaster-information-management-system-the-bipad-portal#:~:text=The%20BIPAD%20portal%20is%20the,prototype,%20with%20limited%20practical%20functionality

Vaidya, R. A., Shrestha, M. S., Nasab, N., Gurung, D. R., Kozo, N., Pradhan, N. S., & Wasson, R. J. (2019). Disaster Risk Reduction and Building Resilience in the Hindu Kush Himalaya. In: Wester, P., Mishra, A., Mukherji, A., Shrestha, A. (eds) *The Hindu Kush Himalaya Assessment*. Springer, Cham. https://doi.org/10.1007/978-3-319-92288-1_11

Vaidya, R.A., Shrestha, A.B., Nepal, S., and Shrestha, K. (2022). *The Koshi River Basin: Insights into biophysical, socioeconomic, and governance challenges and opportunities - Resource Book.* International Centre for Integrated Mountain Development (ICIMOD). https://doi.org/10.53055/ICIMOD.1008

Wagner, M. (2023). *'Early Action: The State of Play 2022'*, Risk-informed Early Action Partnership, Geneva. https://www.early-action-reap.org/early-action-state-play-2022

Wang, W., Zhang, T., Yao, T., An, B. (2022). Monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas. International Journal of Disaster Risk Reduction, 73. https://doi.org/10.1016/j.ijdrr.2022.102914.

Wassénius, E., and Crona, B.I. (2022). Adapting Risk Assessments for a Complex Future. *One Earth, 5*, 35-43.

Watanabe, T., Lamsal, D., and Ives, J.D. (2009). Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu

Himal, Nepal. *Norwegian Journal of Geography, 63*(4), 255-267. https://doi.org/10.1080/00291950903368367

Watanabe, T., Byers, A.C., Somos-Valenzuela, M.A., McKinney, D.C. (2016). The Need for Community Involvement in Glacial Lake Field Research: The Case of Imja Glacial Lake, Khumbu, Nepal Himalaya. In: Singh, R., Schickhoff, U., Mal, S. (eds) *Climate Change, Glacier Response, and Vegetation Dynamics in the Himalaya*. Springer, Cham. https://doi.org/10.1007/978-3-319-28977-9_13

Weingärtner, L., Pforr, T., and Wilkinson, E. (2020). *The evidence base on Anticipatory Action*. World Food Programme.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., Reynolds, J. M., Hassan, M. A., & Lowe, A. (2015). Numerical modelling of glacial lake outburst floods using physically based dam-breach models. *Earth Surface Dynamics, 3*(1), 171-199.

Wieringa, R.J. (2014). *Design Science Methodology for Information Systems and Software Engineering*. Springer-Verlag: Berlin Heidelberg.

World Meteorological Organization (2017). *Multi-Hazard Early Warning Systems: A Checklist*. Multi-Hazard Early Warning Conference, Geneva. Accessed via: https://library.wmo.int/doc_num.php?explnum_id=4463

Zhang, T., Wang, W., Gao, T., & An, B. (2021). Simulation and assessment of future glacial lake outburst floods in the Poiqu river basin, Central Himalayas. *Water, 13*(10), 1376.