# Understanding Water-related Multi-hazards in a Sustainable Development Context


Julia Mary Docherty


A thesis submitted to the University of Birmingham for the degree of

DOCTOR OF PHILOSOPHY


School of Geography, Earth, and Environmental Science

College of Life and Environmental Sciences

University of Birmingham


December 2022

# Abstract

Water-related multi-hazards have devastating impacts on people around the world. Interdisciplinary research is required, especially in data limited lower- and middle-income countries, on multiple hazards to improve our understanding of space-time patterns and controlling processes. In this thesis, a novel framework for studying water-related multi-hazards in a sustainable development context is proposed which provides a powerful tool for analysis and knowledge advancement. Using Nepal as a case study, the framework is applied to investigate the patterns of (co-)occurrence and potential drivers of water-related multi-hazards. In addition, a narrative review is used to conceptualise social vulnerability and recognise the importance of a place-based approach to multi-hazard research. It was found that there is space-time variation in the occurrence and co-occurrence of water-related multi-hazards that appears to be driven by a combination of factors, including large-scale climate, local hydrometeorology, landscape characteristics, and anthropogenic activity. An evaluation of social vulnerability revealed that it is shaped by place-based issues, including coping strategies, and propagates from the intertwining of social and physical processes that arise from multiple scales. This new understanding has potential transferability to a range of multi-hazard contexts and settings worldwide and for use by stakeholders to reduce disaster risk and promote sustainable development.

# Acknowledgements

I would like to start by sincerely thanking my supervisors, Prof. David M. Hannah and Dr. Julian R. A. Clark at the University of Birmingham. This would not have been possible without your guidance and support throughout. In addition, I would like to thank Dr. Feng Mao at the University of Warwick who gave valuable advice.

I would also like to thank Dr. Simon Allen and Alberto Muñoz-Torrero Manchado at the University of Geneva for your supervision during placements at the University of Geneva in 2019 and 2020. You were a source of knowledge and ideas and your tuition in ArcGIS was crucial to the work presented in Chapters 3 and 4.

I also acknowledge the financial support I have received from the UK's NERC Science for Humanitarian Emergencies and Resilience (SHEAR) program, under their SSC doctoral training programme.

Additional thanks to my family friends in Birmingham. To all of the Greens, you have been an amazing source of fun and have really looked after me during my time in Brum. Thank you to my brother, Rob, for always being there and thank you to my sister, brother-in-law and nephews, Fi, Josh, Rory, and Ethan, for not only putting a roof over my head for the final months but providing an unbelievable amount of encouragement and support.

Finally, and most importantly, I would like to express my gratitude to my parents, Hilary and Kevin, who have been there for me and believed I could do this even when things got tough.

# Contents

# Figures

# Tables

# Acronyms

| | |
|---|---|
| ADPC | Asian Disaster Preparedness Centre |
| AHP | Analytical Hierarchy Process |
| ANOSIM | Analysis of Similarities |
| APHRODITE | Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation |
| CHIRPS | Climate Hazards Group InfraRed Precipitation |
| DEM | Digital Elevation Model |
| DesInventar | Disaster Inventory System |
| DFO | Dartmouth Flood Observatory |
| DHM | Department of Hydrology and Meteorology |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| ENSO | El Niño-Southern Oscillation |
| EM-DAT | Emergency Events Database |
| ERA5 | ECMWF Atmospheric Reanalysis Version 5 |
| EWS | Early Warning System |
| FGD | Focus Group Discussion |
| GIS | Geographical Information System |
| GLFD | Global Landslide Fatality Database |
| GoN | Government of Nepal |
| GLM | Generalised Linear Model |
| GPM | Global Precipitation Measurements |
| HDI | Human Development Index |
| HIC | High Income Country |
| ICIMOD | International Centre of Integrated Mountain Development |
| ICT | Information Communication Technology |
| IMERG | Integrated Multi-Satellite Retrievals for Global Precipitation Measurement |

| | |
|---|---|
| LIC | Low Income Country |
| LMIC | Lower- and-Middle Income Country |
| NCEI | National Centres for Environmental Information |
| NGO | Non-governmental Organisation |
| NLCMS | National Land Cover Monitoring System |
| NHRA | Nepal Hazard Risk Assessment |
| PCA | Principal Component Analysis |
| SFDRR | Sendai Framework for Disaster Risk Reduction |
| SOI | Southern Oscillation Index |
| SRTM | Shuttle Radar Topography Mission |
| SVM | Support Vector Model |
| TRMM | Tropical Rainfall Measuring Mission |
| UMIC | Upper- and Middle- Income Country |
| UNISDR | United Nations International Strategy for Disaster Reduction |

# Chapter 1 - Introduction

## 1.1. Background and rationale

In this thesis, the term ‘water-related multi-hazards' refers to hydrologically induced landslides and flooding. The co-occurrence of these hazards is common in many parts of the world, particularly mountainous regions where there are steep sided slopes and narrow river channels upstream and flat floodplains downstream (Bischiniotis et al., 2018). There are many adverse social and economic effects caused by these hazards including death, injury, property damage, and disruption to agriculture (Cieslik et al., 2019; Nayava et al., 2022). These issues are most pertinent in lower- and middle-income countries (LMICs) where there are high levels of social vulnerability related to poverty, inequality, and illiteracy, in addition to the challenges presented within evolving governance systems (Samir, 2013; Vij et al., 2020). Furthermore, they create a barrier to development and restrict progress towards achieving the United Nations' Sustainable Development Goals (UNISDR, 2015).

There is often a data shortage in these countries due to a lack of resources and training (Butte et al., 2022) . This is evident in mountainous regions of LMICs where there is limited access for fieldwork (Jansky et al., 2002). This can be overcome by using publicly available hazard inventories and remote sensing (Froude and Petley, 2018; van Westen et al., 2014).  Water-related multi-hazards are related to hydrometeorology which is affected by changing climate and weather systems (Gallina et al., 2016; Nayava et al., 2022). Thus, we must further our knowledge and understanding of these multi-hazards to reduce disaster risk and promote sustainable development in a rapidly changing climate.

The current understanding of multi-hazards has developed over time. The “all-hazards-at-a-place” approach, conceptualised by Hewitt and Burton (1973), was the first to consider the combination of all hazards within an environment. Lewis (1984) followed the same principles using the term “multi-hazard”. Since this time, there has been research on a whole suite of multi-hazards from coastal, volcanic, seismic, and mountain environments. Generally the term can be interpreted as the consideration of multiple hazards posing risk to a certain area under observation (Eshrati et al., 2015).

Different multi-hazard relationships are described in the literature which all involve the co-occurrence of hazards. In some cases one hazard can be triggered by another in a domino or cascading effect (Eshrati et al., 2015). In other cases, the occurrence of one hazard significantly increases the likelihood of another. This can be termed a coupled multi-hazard interaction or an amplification relationship (Korswagen et al., 2019). In this relationship, the impact of subsequent hazards is dependent on the outcome of the first hazard (Korswagen et al., 2019). There are also compound hazards which are the simultaneous occurrence of multiple hazards. This coincidence of two independent hazards causes impacts greater than the sum of the two (Ciurean et al., 2018). Hazards can also occur cumulatively over time causing additive effects (Eshrati et al., 2015). It must also be considered that the mitigation of one hazard by human intervention may intensify the impacts of another (Yousefi et al., 2020).

There are a range of approaches to describe the relationships between multi-hazards, such as narrative descriptions (Han et al., 2007), hazard matrices (Gill and Malamud, 2014), and network diagrams (van Westen et al., 2014). These methods are useful for understanding hazard interactions but give no evaluation of risk.

A common approach to hazard risk assessment is the creation of hazard maps (Bathrellos et al., 2017; Johnson et al., 2016; Khaing et al., 2019; Shrestha, 2002). Individual hazard maps are created from GIS analysis and the weighting of various factors related to the likely occurrence of a hazard event (Shrestha, 2002). In some cases these individual hazard maps are combined to produce multi-hazard maps (Bathrellos et al., 2017). These maps provide a valuable tool for locating areas with high levels of risk. However, they give no element of the timing of hazards and do not fully account for the key drivers (Khaing et al., 2019).

Another approach to characterising multi-hazard environments is the development of hazard indices. Indicators related to exposure and sensitivity to hazards are standardised and then aggregated to give a multi-hazard impact index which can be used to explore the interactions between indicators that influence the index (Ciurean et al., 2018).

Physical models have also been developed to understand multi-hazards and their interactions (Chen et al., 2021). Machine learning models, such as the generalised linear model (GLM) or the support vector machine (SVM), are often used to statistically analyse the different factors related to hazard occurrence (Yousefi et al., 2020). There are also probabilistic approaches which assess the likelihood of risk scenarios using differing levels of information regarding hazard interactions (Mignan et al., 2014). A limitation of these methods is that they are usually only applied to simulated environments, rather than actual geographic contexts.

There have been many studies using rain gauge data and satellite derived rainfall products that analyse the space time distribution of precipitation (Duncan and Biggs, 2012; Krakauer et al., 2013). Kansakar et al. (2004) evaluated the spatial pattern of the precipitation regime in Nepal from weather station data and found that the movement of the South Asian Monsoon and the topography were key controls, but they did not relate this to the hazard occurrence. There are many other studies that do relate landslides or flooding to rainfall (Berti et al., 2012; Dahal and Hasegawa, 2008).

The most commonly used tool for predicting the possible occurrence of a landslide or flood is rainfall threshold analysis (Golian et al., 2010; Martina et al., 2006; Segoni et al., 2018). In a study in China, Miao et al. (2016) established rainfall thresholds for flood warnings based on a hydrological model and Zêzere et al. (2015) used past landslide events in an analysis of landslide rainfall thresholds in Portugal. These studies provide information for the forecasting of single hazards but they do not relate precipitation trends to both landslides and flooding and therefore do not account for the co-occurrence and interactions between these hazards (Chen et al., 2016; Gaire et al., 2015). Furthermore, landslides and flooding are often analysed separately due to different hazard types requiring different methods of analysis and the difficulty of accounting for relations and interactions between them (Kappes et al., 2012).

The concept of social vulnerability to multi-hazards has been reviewed extensively in the literature yet it is still poorly defined and broadly conceptualised (Cutter et al., 2003). Blaikie et al. (1994) and Cutter (1996) are examples of publications which highlight the importance of understanding and evaluating the social vulnerability to natural hazards. In particular there is a lack of focus on social vulnerability to multiple hazards which differs from the social vulnerability to single hazards (Drakes and Tate, 2022).

The inclusion of a social science perspective in the assessment of floods and landslides has become increasingly important (Xu et al., 2018). There are many theoretical and empirical approaches to the evaluation of social vulnerability (Blaikie et al., 1994; Guillard-Gonçalves and Zêzere, 2018). Several case studies in Nepal use social vulnerability indexing based on socio-economic factors (Aksha et al., 2019; Bista, 2019; Gautam, 2017). Gautam (2017) for example quantified social vulnerability in Nepal and found that the majority of the country has a moderate to high level of social vulnerability. Aksha et al. (2019) used social vulnerability indexing to analyse the spatial vulnerability to natural hazards across Nepal. These analyses are valuable at the broad scale but do not account for the specificity of places. The concept of place and place-attachment are imperative to understanding how people cope with the challenges of multi-hazards (Swapan and Sadeque, 2021).

The ‘disaster pressure and release’ model devised by Blaikie et al. 1994 suggests ways in which both social and natural processes can be combined (Wisner, 2004). However, there are still gaps in the existing knowledge surrounding the interconnections between social vulnerability and the physical environment. Therefore, it is important to understand the space-time patterns of these multi-hazards in relation to hydrometeorological drivers and basin properties, in addition to recognizing the importance of social vulnerability in a place-based approach.

As such, this is an interdisciplinary thesis that synthesises both environmental and social aspects in our evaluation of water-related multi-hazards using Nepal as a case study.

## 1.2. Nepal case study

In Nepal, multi-hazards cause over 100 fatalities and millions of pounds worth of infrastructure damage each year (Adhikari and Adhikary, 2019). Thus, research on multi-hazard processes and social vulnerability has important implications for policy and decision making in this country. Other reasons why Nepal is chosen as an ideal case study include:

1) Nepal has a high exposure to water-related multi-hazards.
2) The presence of the South Asian Monsoon brings extreme and variable hydrometeorology which allows the analysis of rainfall signatures and the effect they have on water-related multi-hazards.
3) Nepal has complex topography with steep sided mountains and wide flat floodplains. This diverse geomorphology acts as a model for mountain research globally.
4) Nepal is a LMIC ranked 143/189 countries (GoN, 2017a). As such, this research demonstrates how to overcome the limited access and availability of data.

Many mountainous regions around the world have a high exposure to water-related multi-hazards including other parts of the Himalayas in India and China, or other mountain ranges like the Alps, the Andes, and the Rocky Mountains. While regions like the Alps see localised landslides and regions of India face occasional large flood disasters, Nepal faces more frequent medium-scale flood and landslide events during the monsoon providing good disaster data. Landslide and flood monitoring are more advanced in regions like Switzerland, Canada, or the United States unlike Nepal where hazards can be more destructive and fatal. Nepal has the combination of poorer infrastructure, challenging terrain, lack of financial resources, and governance challenges that amplify disaster impacts relative to other mountain communities in richer countries.

In summary, while many mountain regions face natural hazard risks, Nepal's convergence of physical and social vulnerability make it one of the most complex, risky and compelling locations for in-depth disaster research aimed at saving lives and climate change adaptation.

## 1.3. Research gaps

Analysis of the multi-hazard literature in Chapter 2 identified four main research gaps which have been addressed throughout the thesis:

**Research gap 1: Analytical framework for understanding water-related multi-hazards in a sustainable development context**

One of the challenges to date is that there is not an appropriate framework to investigate, measure, and model multi-hazards and think beyond the environmental phenomena to include the social vulnerability aspect. This framework would need to outline and recommend a methodology for achieving a place-based approach to multi-hazard research. This is addressed in Chapter 2 with the development of a framework for understanding water-related multi-hazards in a sustainable development context.

**Research gap 2: Single hazard approaches dominate the field**

Landslides and flooding co-occur in many parts of the world, particularly mountainous regions (Bischiniotis et al., 2018). Work on these two hazards is often separated into landslide research (Hovius et al., 1997; Kirschbaum et al., 2020; Petley et al., 2007) and flood research (Adhikari et al., 2010; Gain et al., 2008). In 2015, the United Nations' Sendai Framework for Disaster Risk Reduction (SFDRR) called for a multi-hazard approach (UNISDR, 2015). This is vital in furthering our understanding and insuring there is not an underestimation of disaster risk. Thus, there is a need to analyse the co-occurrence of landslides and flooding as multi-hazards. This is recognised and addressed in all four of the core chapters.

**Research gap 3: LMICs are lacking comprehensive research**

Less research has been conducted in LMICs due to a lack of resources and restricted access to remote environments for primary data collection. Using Nepal as a case study in Chapters 3, 4, and 5 demonstrates work in data-scarce regions of the developing world.

**Research gap 4: Interdisciplinary research is required**

Social relations and the physical environment of multi-hazards are in dialectical tension and must be understood together. This is conceptualised in Chapter 5 with an analysis of social vulnerability and the outlining of a place-based approach.

## 1.4. Research objectives

The overarching aim of the thesis is to better understand water-related multi-hazards in a sustainable development context. This will be achieved according to the following four objectives:

1. To develop a framework for understanding water-related multi-hazards in a sustainable context. This will be addressed in Chapter 2.
2. To investigate the patterns of water-related multi-hazard occurrence and co-occurrence in Nepal. This will be addressed in Chapter 3.
3. To determine the hydrometeorological drivers and river basin controls related to multi-hazards. This will be addressed in Chapter 4.
4. To conceptualise social vulnerability to multi-hazards and outline a place-based approach. This will be addressed in Chapter 5.

## 1.5. Thesis structure

This thesis is made up of six chapters which are interlinked as shown in figure 1.1.

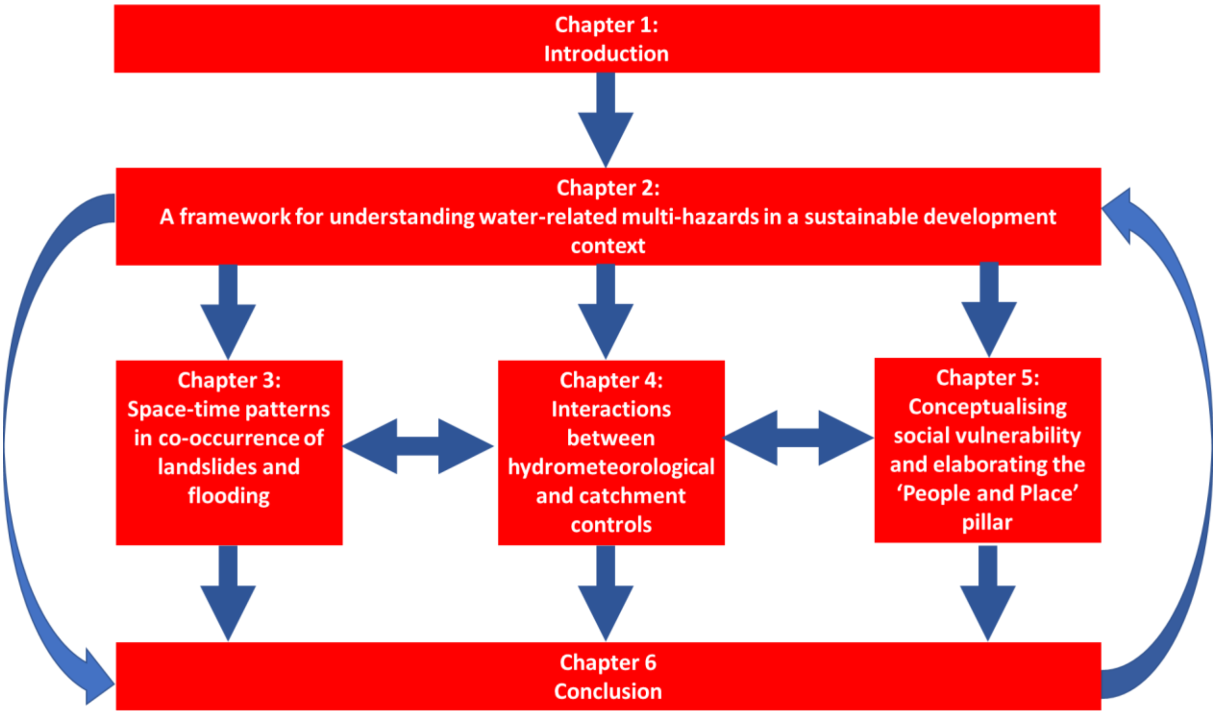


*Figure 1.1. Schematic diagram of the thesis structure. The red boxes show each of the chapter titles and the blue arrows show the interconnections between those chapters.*

Chapter 2 presents a framework developed from a bibliometric analysis of the literature and a critical evaluation of existing approaches. This framework forms the backbone to the thesis which is followed in the subsequent chapters.

Chapters 3, 4 and 5 are the core research chapters of the thesis. Using Nepal as a case study, Chapter 3 evaluates the patterns of multi-hazards and investigates the causative factors related to water-related multi-hazards. Chapter 4 zooms in on this analysis and looks closer at the hydrometeorological drivers and river basin controls that influence the occurrence and co-occurrence of water-related multi-hazards in Nepal. This research has the potential to provide guidance for future modelling and prediction.

The concept of social vulnerability and the approaches used to quantify it were analysed in Chapter 5 along with a focus on a place-based approach. This chapter outlines the reasons for considering communities and the importance of place in multi-hazard research.

Chapter 6 concludes the thesis by modifying the framework, synthesising the findings of the core chapters, and providing recommendations for future research.

The results of this thesis have wide applicability for disaster risk reduction and climate change adaptation. Some of the key benefits and applications are improved disaster preparedness, risk informed development, and community resilience. The knowledge and understanding obtained from this thesis can also be used for modelling and prediction.

In addition, this work has the potential to be applied to other multi-hazard combinations and geographical settings thus reducing disaster risk globally.

## 1.6. Chapter summary

This chapter has introduced the research theme and provided some background on water-related multi-hazards. Research gaps and objectives have been listed that will be addressed in the subsequent chapters as outlined in the thesis structure (Fig. 1.1).

Chapter 2 undertakes a bibliometric analysis and develops a framework for understanding water-related multi-hazards in a sustainable development context. The research in Chapter 2 “A framework for understanding water-related multi-hazards in a sustainable development context" was published in Progress in Physical Geography, this research was also presented in workshops and conferences. The paper can be found at this link: https://doi.org/10.1177/0309133319900926

# Chapter 2 - A framework for understanding water-related multi-hazards in a sustainable development context

**Note, this research has been published in Progress in Physical Geography (Docherty et al., 2020). The publication can be found in the appendix as in this chapter there have been some modifications to the text.**

## 2.1. Abstract

Hazards often do not occur in isolation, and, for this reason, a multi-hazard approach is vital in realising their impact and providing solutions for disaster risk reduction and sustainable development. In this chapter, we present a novel framework that was developed from a bibliometric analysis of the multi-hazard literature and a critical appraisal of the existing approaches. It was found that multi-hazard research has expanded greatly over the last 20 years furthering our understanding of the subject with important applications in risk assessment and management. These studies have contextualised multi-hazards, developed models and frameworks to analyse them, provided case studies to test multi-hazard-based approaches, and latterly produced reviews. It was found that landslides and flooding commonly co-occur within the bibliographic dataset yet understanding of their interactions, hydrometeorological drivers and landscape controls remain poorly conceptualised. Therefore, we propose a new framework for investigating water-related multi-hazards that leverages and

synthesises existing methods to address the challenges identified to date. We also found a geographical bias, with less multi-hazard research in lower- and middle-income countries and remote environments due to data scarcity and limited accessibility. Our framework therefore includes the ability to address geographically specific key considerations including available and accessible data, community variability and cross-sectoral collaborations. In doing so it offers guidance on structuring future analyses to improve our understanding of multi-hazards, reduce disaster risk, increase community resilience, and make progress towards sustainable development. The framework will be used throughout the rest of the thesis with a focus on Nepal as a case study region.

## 2.2. Introduction

Natural hazards have devastating economic, societal, and environmental impacts around the globe (UNISDR, 2015). It has become widely accepted that hazards do not occur in isolation and this realisation is vital in furthering our understanding of natural hazards (Gill and Malamud, 2014). Multi-hazard research is the study of multiple hazards and their interactions within a defined time and space (Kappes et al., 2012). Hewitt and Burton (1973) first proposed the concept of investigating all hazards and environmental parameters within a hazardous environment, followed over a decade later by Lewis (1984) who used the term ‘multi-hazard’ in the analysis of hazards, namely the combination of earthquakes, droughts, and hurricanes in Antigua. These papers set the foundation for a holistic approach to multi-hazard research, in which all hazards are considered together.

Through time, multi-hazard research has evolved with valuable contributions made from a number of disciplinary perspectives. In more recent years, social vulnerability of affected populations has been included in the assessment and management of natural disasters (Blaikie et al., 1994; Cutter, 1996). This research has resulted in an extensive literature, emphasising the need to consolidate findings and identify gaps in existing research through meta-analysis.

Crucial here is enhancing our knowledge of multi-hazards given their role in exacerbating development challenges faced by lower- and middle-income countries (LMICs). These challenges are often intensified by the impacts of intersecting natural hazards, meaning that progress towards achieving the United Nations’ Sustainable Development Goals must involve a comprehensive understanding of multi-hazards, as outlined in the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015). LMICs are impacted most heavily due to high levels of vulnerability related to poverty, inequality, and illiteracy, in addition to the challenges presented within evolving governance systems (Keating et al., 2017). Furthermore, in LMICs, there is a lack of resources and training restricting the quantity and quality of data obtainable (Johnson et al., 2018; Zogheib et al., 2018). This data shortage leads to a paucity in knowledge and understanding (Barrantes, 2018; Uprety et al., 2019).

The threat of climate change further exacerbates these uncertainties, in particular highlighting the increasing dangers of hazards related to hydrometeorology (Gallina et al., 2016; Hannah et al., 2005). Water-related hazards, such as hydrologically induced landslides and flooding, are among the most destructive of these hazard types (Emerton et al., 2016; Shen et al., 2018). A better understanding of water-related multi-hazards is thus vital for implementing effective evidence-based policies for disaster risk reduction, an issue that is particularly pertinent in LMICs (Mignan et al., 2017). However, notwithstanding these geographically defined effects, the fact remains that existing multi-hazard frameworks often fail in characterising the space and time dependent dynamics of the environment and do not always consider the people and places that are affected (Haughton and White, 2018; Pescaroli and Alexander, 2018). Consequently, we argue that it is vital to develop innovative approaches to analysing multi-hazards capable of comprehensively investigating water-related multi-hazards in data-scarce regions of LMICs.

This chapter aims to progress geographic research by yielding valuable knowledge on the current state of work using the term ‘multi-hazard’, in line with the call for a multi-hazard approach in the SFDRR. We have undertaken this task through a structured bibliometric analysis, which provides insights and identifies trends and gaps within a defined literary sample by classifying publications according to factors, such as distributions, focus and authorship (Gao and Ruan, 2018).

The result of these investigations underpins the development of an innovative framework that seeks to advance understanding of multi-hazards in a sustainable development context. Our framework is novel in that it takes a place-based approach to address the full complexity of a multi-faceted system and unites theories and methodologies from differing perspectives and skillsets overcoming the challenges and limitations of multi-hazard research.

## 2.3. Data and methods

For this chapter, bibliometric analysis techniques, adapted from previous studies, were applied in order to understand the scope and evaluate trends in the multi-hazard research (Karpouzoglou et al., 2016; Stewart, 2011; Xu et al., 2018). The literature was distilled to provide a representative sample and analysed according to application and orientation, collaborative networks and their temporal, spatial, economic, and environmental distribution (Fig. 2.1). The spatial, economic, and environmental distribution were investigated to discover areas that have been less intensively studied, whilst term co-occurrence maps were used to analyse the focal topics of the research. The outcomes of this analysis provide the evidence base to re-think and focus a new framework.

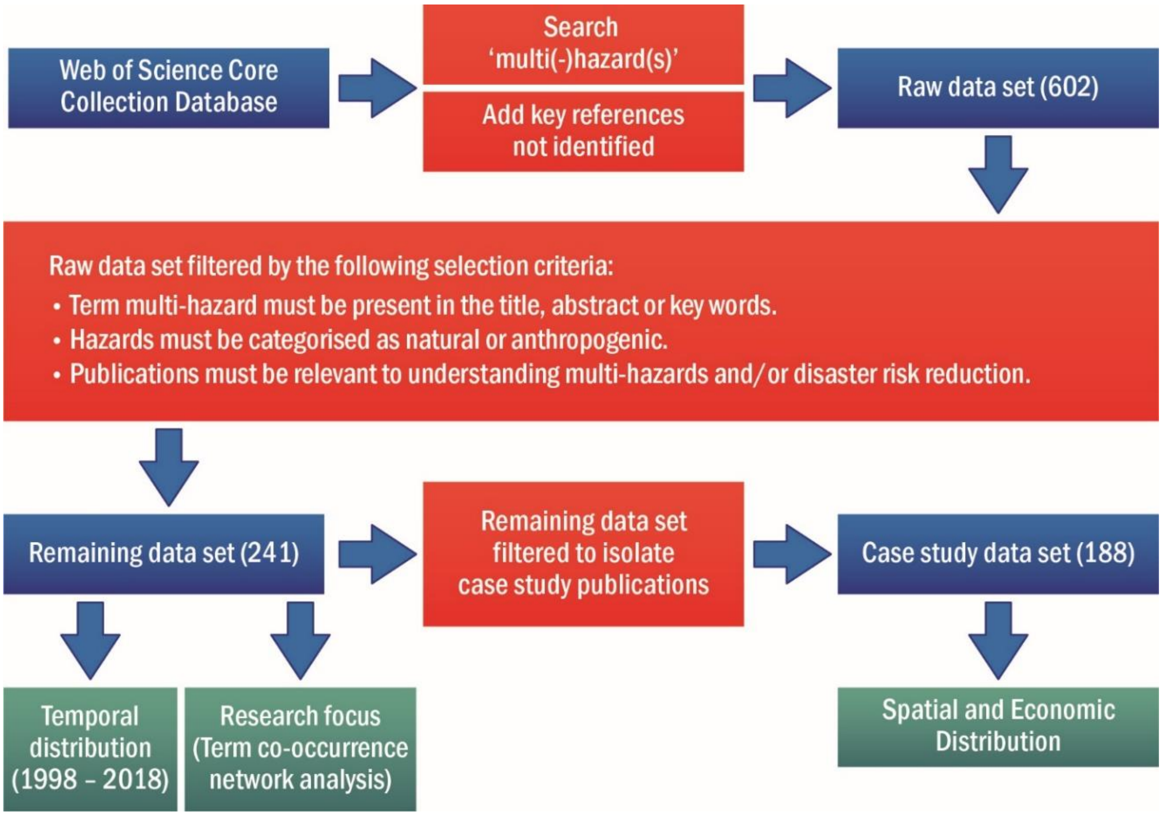


*Figure 2.1. Schematic flow diagram of the selection of bibliometric data sets and analysis performed in 2018. The blue boxes indicate data sets, the red boxes are actions taken to filter those data, and the green boxes show the analysis undertaken. The results of this analysis cannot be repeated due to the timing of the publications and the availability of software.*

The *Web of Science Core Collection* database was used to find the available academic literature in the area of multi-hazard research. The initial search used the term '*multi(-)hazard(s)*' in the topic of the publications and generated a raw data set of 602 results starting with the first paper to mention multi-hazards (Lewis, 1984), extending to 2018, the most recent at the time of the search [data accessed 14/01/2019]. The results were read, evaluated, and filtered according to a set of selection criteria; publications were only included if the term multi-hazard was present in the title, abstract and/or key words, the hazards mentioned could be categorised as natural or anthropogenic and the publications were relevant to understanding multi-hazards and/or disaster risk reduction. From the raw data, 60% of publications were excluded as they were related to healthcare, social care, terrorism, and infrastructure reinforcement. Additional key references in the field, not identified through the initial search, but highly cited within the remaining publications were added subsequently following the methods of Karpouzoglou et al. (2016). This included Hewitt and Burton (1973), a highly cited paper describing the concept of 'all-hazards-at-a-place' without using the term 'multi-hazard' and a number of highly cited papers using the synonyms, cascading and/or compound hazards. This protocol narrowed the dataset to publications specific to this study and key to developing a new framework for disaster risk reduction.

The resulting 241 papers formed the bibliographic data set which was first analysed according to temporal distribution. Number of publications through time, based on the year of publication, were plotted to investigate the temporal trend from 1998 - 2018. This time frame was selected because only two articles were published before 1998, namely Hewitt and Burton (1973) and Lewis (1984). These have not been included in this sample due to the sparse level of publication between 1971 and 1998 as single hazard approaches were dominating the field.

Of the 241 publications, 188 were research articles set in specific case study locations. The 46 remaining publications included comparative studies, broad scale global analysis and conceptual review papers. Case studies were identified individually by finding and noting references to study locations and also the location of the institute conducting the research. This generated data to analyse the spatial distribution and economic level of the case study areas and a comparison with where the researchers had published. The level of economic development of each country was based on the World Bank 2018-2019 country classifications (World Bank, 2018). The information on study location was coupled with the location of publication to evaluate global north to global south distributions in research.

The bibliographic data set of 241 papers was also analysed according to overall focal topic. This was done by creating a term co-occurrence map based on text data, generated using VOSviewer version 1.6.9 (van Eck and Waltman, 2018). The minimum number of occurrences of a term was set to 10 and of the 15,080 terms detected, 237 met this threshold. Irrelevant terms, such as case study locations, highly cited author names, journal titles and words present in all texts were filtered before the map was generated.

In addition to finding these trends, the identified literature was also critically analysed to evaluate the key themes, major challenges, and existing approaches. The literature attributes from nine highly cited publications were identified and displayed in table form. The analysis of this data using the methods stated was intended to provide a comprehensive overview of the multi-hazard literature and identify the challenges and key considerations for developing a framework.

## 2.4. Bibliometric analysis and interpretation

### 2.4.1. Spatial and temporal distribution

The temporal distribution of publications related to understanding multi-hazards and disaster risk reduction between 1998 and 2018 is shown in Figure 2.2. Although single hazard approaches still dominate the field, we find an overall increasing trend in multi-hazard publications over this 20-year period characterised by a slow progression between 1998 and 2010 followed by a marked increase. This is a significant trend considering that the total number of publications has also increased through time. The scientific community gradually began to focus on multi-hazards from around 2003, Kappes et al., (2012) defined the term multi-hazard, which made a significant impact on the temporal distribution of the literature (Fig. 2.2). The introduction in 2015 of the SFDRR, which calls for a 'multi-hazard' approach in relation to disaster risk reduction, may have had some impact on increasing multi-hazard publications as there is a sharp increase from 2015 to 2016 (Fig. 2.2). In 2018 alone, 57 articles were published related to understanding multi-hazards and disaster risk reduction.

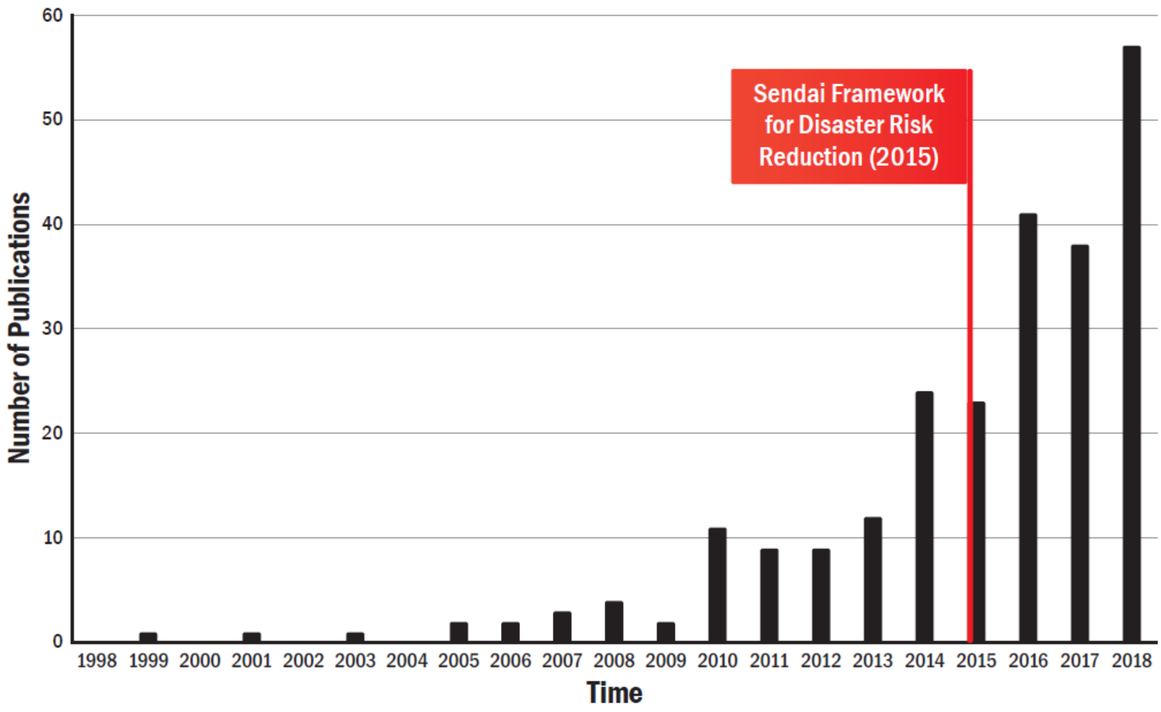


*Figure 2.2. Temporal distribution of reviewed multi-hazard publications between 1998 and 2018. The red bar shows the Sendai Framework for Disaster Risk Reduction (SFDRR).*

We identify a number of reasons for the increase in the number of publications on this topic over the past 20 years, indicating the increasing recognition and importance of investigating multi-hazard environments. Climate change, increasing climate variability and the occurrence of extreme events linked often to devastation to human environments has encouraged research on natural hazards (Sullivan-Wiley and Gianotti, 2017). In addition, over time, there has been increased understanding that hazards do not tend to act in isolation and thus a multi-hazard approach is required. This has been internationally recognised and published in strategy and policy documents, including the SFDRR (UNISDR, 2015). It must also be noted that the rate of publication has increased with time and may also be responsible for the trend.

Analysing the spatial distribution of multi-hazard case studies shows that the highest density is in Europe, representing 30% of all studies (Fig. 2.3). The countries with the highest total number of case studies are China, USA, Italy, and India. Further analysis of the localities shows the majority of research has taken place in higher-income countries (HIC) rather than those with a lower income (Fig. 2.3). Authorship analysis showed that in 66% of the publications the area studied is in the same country as the institute of the first author. This indicates that research has tended to be conducted by local researchers, rather than an international focus from countries in the global North on countries in the global South.

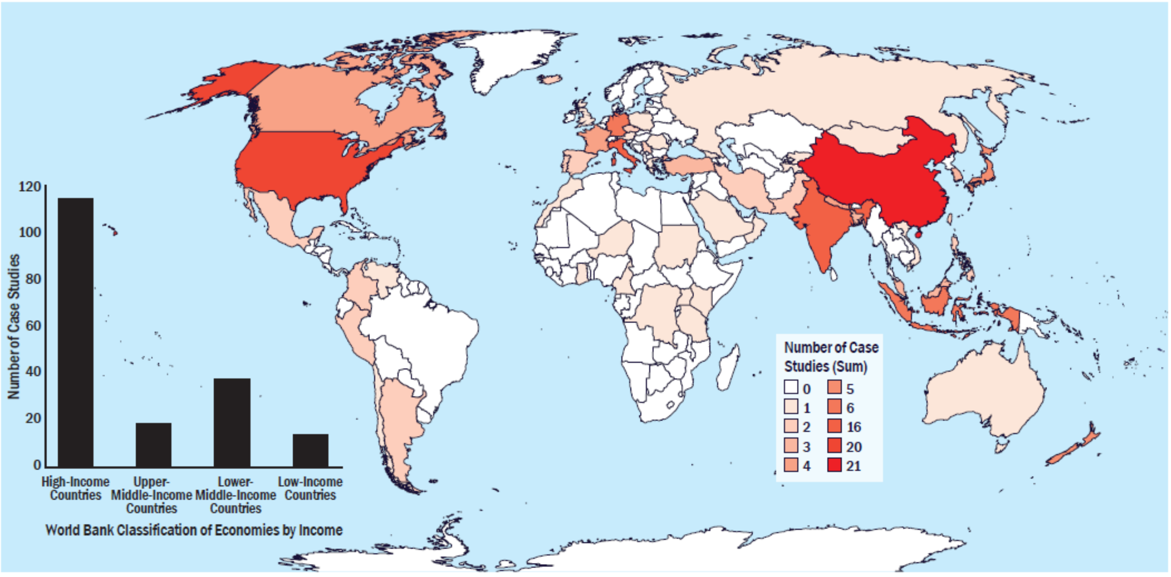


*Figure 2.3. Spatial distribution of multi-hazard case studies and chart of case studies by level of economic development. The countries were classified according to the World Bank 2018-2019 as high-income countries (HICs), upper- and middle-income countries (UMIC), lower- and middle-income countries (LMICs), and low-income countries (LICs).*

This analysis shows that multi-hazard environments in HICs have been studied more intensively than those in LMICs. However, it is possible that the size of the country could reflect the number of publications, nevertheless it still remains that LMICs like Nepal have a high number of publications especially considering size. Our analysis suggests that this results from there being a higher quantity of reliable data available in HICs and that in these countries it is easier to access remote areas and conduct fieldwork for sourcing primary data (Petley, 2010). Thus, we argue that we need to balance the spatial distribution of multi-hazard research and ensure that the understanding of hazard-prone environments in LMICs is not limited by access and availability of data.

In addition, channels of communication between citizens and authorities are better developed in HICs, resulting in a greater response to knowledge generated for disaster risk reduction (McCallum et al., 2016). These data-intensive and cooperative systems have enabled most communities in HICs to develop strategies for coping with natural hazards and building the resilience for effective recovery. This must be a priority outcome for development of a framework focused on remote data-scarce regions of LMICs.

### 2.4.2. Focal topics

Analysis of the occurrence of frequently used terms within the text data is useful for realising the key focal topics within the refined literature. A term co-occurrence network diagram and a chart of the most frequently occurring hazard terms based on text data from the refined data set is shown in Figure 2.4. The different colours on the diagram show three distinct clusters of related terms. In red, we have key quantitative methods and techniques for addressing disaster risk reduction, namely ‘GIS’, ‘remote sensing’, ‘probability’, ‘model’ and ‘mapping’, which have strong linkage with the hazards ‘volcano’ on one side and ‘tsunami’, and ‘storm surge’ on the other. At the top of the diagram, the blue cluster with multiple linkages across the figure sets out instrumental hazard terms ‘earthquake’, ‘landslide’, ‘flood’, and ‘fire’, which are strongly linked to ‘multidisciplinary’ and ‘response’. On the right-hand side of the diagram there is the green cluster which highlights critical social themes including ‘education’, ‘community’, ‘vulnerability’, ‘resilience’, ‘exposure’, and ‘adaptation’. Within this green cluster, ‘climate change’ and ‘drought’ are highly linked with these themes.

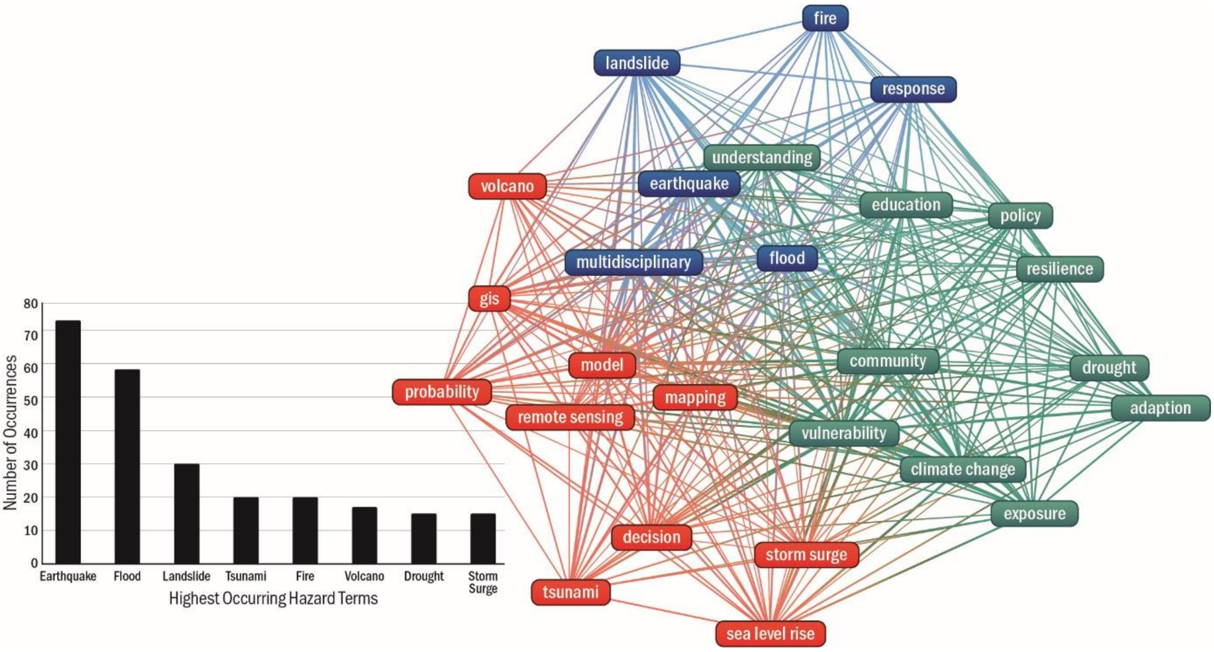


*Figure 2.4. Term co-occurrence network diagram based on text data and chart of the most frequently occurring hazard terms. The boxes represent frequently occurring terms and the lines that link the nodes represent the co-occurrence of terms within publications. The position of terms within each of the coloured clusters shows that these terms are strongly linked, appearing in publications together, and relating to each other.*

Investigation of the occurrence of individual hazard terms at a minimum of five occurrences showed that the terms ‘earthquake’, ‘flood’, and ‘landslide’ had the highest number of occurrences and were closely related. The terms ‘flood’ and ‘landslide’ have a high link strength, which means that they often occur in the same articles. This indicates that much of the multi-hazard literature focuses on these hazards and regions where they are both present.

The focal topics of the bibliographic data therefore fall into different disciplines and categories. We argue that these themes are important to disaster risk reduction and must be brought together and considered from the outset in the development of our framework.

Hazard term analysis has highlighted that hydrometeorological processes, specifically landslides and flooding, were highly occurring hazards and strongly linked. Landslides and flooding have a strong linkage because they have a number of factors in common. They occur side by side in mountainous regions and often affect the same populations, the combined force of these two hazards leads to the highest level of economic damage and mortality (Shen et al., 2018). Both hazards are driven by precipitation and controlled by the landscape properties, yet there remains a poor understanding of the direct correlation and information on how they interact (Devkota et al., 2014; Kirschbaum et al., 2012). Climate change is associated with more severe weather events, which is likely to increase the devastation caused by flooding and hydrologically induced mass movements in the future. We argue that it is necessary to better understand the processes related to landslides and flooding in order to mitigate this risk. Thus, we have focused our framework on understanding water-related multi-hazards.

The critical analysis also found that there were many publications focused on the distribution of landslide events and the thematic grouping of different types of mass movements, in which flooding did not feature (Chen et al., 2016; Galli et al., 2008). In some cases, this was because the one occurs without the other as is the case in many regions, such as parts of the Alps and Pyrenees (Papathoma-Köhle et al., 2011; Turconi et al., 2015). van Westen et al (2014) effectively group and analyse rock falls, debris flows, surficial landslides, and slow-moving landslides separately. This has a significant impact on our understanding of multi-hazards and implications for disaster risk reduction and therefore must also be a consideration within our framework.

Much of the research centred around landslide-prone areas of south Asia focus predominantly on landslide risk (Berti et al., 2012; Dhital et al., 1993; Kucera et al., 2012; Petley et al., 2007). Within these complex systems, antecedent rainfall accumulation and previous hazard occurrence can be responsible for priming more hazards (Ruiz-Villanueva et al., 2017). For example, the gravitational mass movement of water-logged slopes, slope instability caused by undercutting by floodwaters, and sediment-dammed landslide lake outburst floods (Allen et al., 2016). Other significant drivers include earthquake occurrence, over-grazing and vegetation removal, land-use change and the construction of infrastructure such as roads (Dai et al., 2002; Sudmeier-Rieux et al., 2019). There is a gap in the literature in which to explore the co-occurrence of both landslides and floods and a new framework is required to further our knowledge by identifying rainfall signatures driving these multi-hazards and evaluating the extent to which basin characteristics moderate the landscape response.

### 2.4.3. Literature attributes

Attributes of the literature were analysed according to a set of comparison criteria. The following tables display this analysis with five examples of the most highly cited review papers (Table 2.1) and four examples of highly cited case studies from the multi-hazard literature (Table 2.2).

*Table 2.1. Literature attributes table comparing key multi-hazard reviews using a set of comparison criteria.*

| **Multi-hazard review** | **Methods or model applied** | **Strengths and challenges** |
|---|---|---|
| Blaikie et al. (1994) | 'Disaster pressure and release' model. | Recognises and outlines that there is both a socio-economic and natural side to disasters.<br><br>Does not outline multi-hazard approach yet has potential to be applied to multiple hazards. |
| Cutter, (1996) | 'The hazards of place' model of vulnerability. | Considers hazard potential from geographical context and social vulnerability.<br><br>Although facilitating multi-hazard approaches, there is no insight into multiple hazard interactions. |
| Kappes et al. (2012) | Examining hazard interactions through binary and descriptive matrices. | Defines and calls for an integrated multi-hazard approach.<br><br>Does not consider people and place, although has the potential to be applied to multidisciplinary frameworks for understanding multi-hazards. |
| Gill and Malamud (2014) | Identification and visualisation of hazard interactions. | Supports a wider understanding of interactions, although is restricted to sequential or cascading hazards.<br><br>Does not consider people and place, although has the potential to be applied to multidisciplinary frameworks for understanding multi-hazards. |
| Pescaroli and Alexander (2018) | Scenario building and vulnerability assessments.<br><br>Identification of thresholds/tipping points. | Supports an understanding and visualisation of the build up to high impact events considering societal consequences. |

*Table 2.2. Literature attributes table comparing key multi-hazard case studies according to a set of comparison criteria.*

| **Multi-hazard case study** | **Location** | **Methods or model applied** | **Strengths and challenges** |
|---|---|---|---|
| Hewitt and Burton (1973) | Ontario, Canada | 'All hazards at a place'<br><br>Multi-hazard mapping | Holistic approach to natural hazards in which human response is also incorporated.<br><br>Provides good foundation although specific techniques are now dated. |
| Carreño et al., (2007) | Bogota, Colombia and Barcelona, Spain | Multi-hazard assessment based on physical and socioeconomic indicators. | Multi-disciplinary evaluation that considers direct physical damage and social fragility.<br><br>Indicators are applied to single hazards and then combined which does not allow for interactions/feedbacks between hazards. |
| Bathrellos et al., (2017) | Peloponnesus, Greece | Multi-hazard susceptibility mapping. | Comprehensive spatial representation of multiple hazards but does not consider the social fabric.<br><br>Overlapping hazards opposed to understanding and representing hazard interactions in time and space. |
| Depietri et al. (2018) | New York City, USA | Multi-hazard vulnerability mapping with socio-economic indicators based on surveys and weighting from local expert opinion. | Strong contribution specific to urban multi-hazard situation.<br><br>Overlapping hazards rather than integrated multi-hazard approach, therefore does not consider interactions/cascades between hazards. |

The approaches to multi-hazard research have been reviewed extensively (Gill and Malamud, 2014; Kappes et al., 2012; Pescaroli and Alexander, 2018). It was found that all the review papers in Table 2.1 call for an integrated multi-hazard approach or have the potential for this approach to be applied. The selection of example review papers range in their focus from Blaikie et al (1994) and Cutter (1996) in which social vulnerability is given an equal importance to the geographic context, to Kappes et al (2012) and Gill and Malamud (2014) which focus more on the quantitative methods of understanding multi-hazard interactions.

Kappes et al (2012) focuses multi-hazard research on an all-inclusive examination of the whole range of natural hazards present. Gill and Malamud (2014) provide a network for visualising cascading interactions between 21 natural hazards. These include earthquake, tsunami, volcanic eruption, landslide, snow avalanche, flood, drought, regional subsidence, ground collapse, soil (local) subsidence, ground heave, storm, tornado, hailstorm, snowstorm, lightning, extreme temperature (hot), extreme temperature (cold), wildfire, geomagnetic storm, and impact event, which are divided into six major hazard groups, namely geophysical, hydrological, shallow earth processes, atmospheric, biophysical, and space. This concept is explored further in Gill and Malamud (2017), in which 18 anthropogenic process types are combined into the matrix, examples include groundwater abstraction, material injection, vegetation removal, infrastructure construction, chemical explosion, and fire. These more quantitative papers lack a social vulnerability component, however the mathematical principles can be used in the application of a multidisciplinary framework for understanding multi-hazards. Pescaroli and Alexander (2018), the most recent review, takes a holistic approach and supports an understanding and visualisation of the build up to high impact events considering societal consequences.

In most circumstances the key information required for disaster risk reduction are predictions of where, when, and the magnitude of the hazard extent (W. Liu et al., 2018). GIS hazard maps are a useful tool for communicating the intensity and distribution of 'risky spaces' (Haughton and White, 2018). They provide a visual representation of hazard predictions that can be used for implementing policy (Carpignano et al., 2009). Furthermore, Early Warning Systems (EWS) inform people at risk of natural hazards in advance of an event, giving people time to prepare and/or evacuate. They are based on the identification of threshold criteria for failure, according to the Cumulative Act Effect Model also known as the Swiss cheese model (Reason, 1990). In this model, when multiple factors align in a specific way, a reaction, in this case a hazardous event, is likely to take place. Real-time and historical data sets can be used to identify the points at which the environmental and societal data reach a tipping point at which these events occur. These resources are important for building community resilience and disaster preparedness (Gautam and Dulal, 2013; Pei et al., 2014; Smith et al., 2017).

Hewitt and Burton (1973) and the other case study papers outlined in Table 2.2 use multi-hazard mapping. These provide an effective spatial representation to predict the timing and impacts of multiple hazards, however this layering of multiple hazards does not promote an understanding of the complex interactions and cascades between hazards. There needs to be a framework which supports an integrated multi-hazard approach in which the feedbacks and interactions between hazards are understood.

The social vulnerability of the affected people must also be understood and analysed within a new framework according to existing analytical methods (Gautam, 2017; Shrestha, 2002). Blaikie et al (1994) introduced the 'pressure and release' model which explains the preliminary driving processes that give rise to vulnerability in hazardous settings, for example exposure. Cutter (1996) builds upon this in the 'hazards of place' model in which the social fabric is explored in more depth and related to the geographic context. In this model, the vulnerability is not fixed in time and can adjust according to changes in the risk, mitigation, and context of the environmental hazards. This literature will be explored further in Chapter 5.

Concurrently, we argue that physical attributes of multi-hazard environments must be investigated alongside their interactions with people and place (Aksha et al., 2018; Cutter et al., 2008). The value of bringing the physical and social together in this way gains a better understanding of the actualisation of hazards as risky events for different social groups in particular places. Hazard mortality and level of economic damage can be used for spatially and temporally representing the intensity and frequency of hazards and how they correlate (Mysiak et al., 2018; Skilodimou et al., 2019). This can be combined with social vulnerability indexing from socio-economic and demographic data to better understand the relative vulnerability to environmental hazards (Cutter et al., 2003). On a broader scale, power relations, prevailing social structures, access to resources, political influences, and socio-economic development of a place are all factors that underlie vulnerability to natural hazards and therefore must also be considered (Blaikie et al., 1994; Pescaroli and Alexander, 2016). In particular, a framework is required to build upon these place-based approaches and provide new insights into multi-cascading risky events like landslides and flooding.

## 2.5. The need for an analytical framework

The preceding analysis strongly suggests that there is a need for developing an alternative framework for investigating water-related multi-hazards, based upon the identification of specific key factors. Bibliometric analysis and critical evaluation of the literature identified a growing focus on multi-hazard research and a shift towards multi-disciplinary approaches in which the social vulnerability of the impacted people are given an equal platform to the drivers of hazards within the environment (Beccari, 2016; Birkmann, 2006; Cutter et al., 2003; Rufat et al., 2015). There were two significant research gaps identified. The first is that there is less multi-hazard research in LMICs and remote environments due to data scarcity and limited accessibility. The second is that there is a limited understanding on the interactions between water-related hazards, specifically landslides and flooding, their hydrometeorological drivers and other controlling factors. Thus, the development of a new framework must build upon these multi-disciplinary approaches with a fresh perspective on landslides and flooding whilst addressing the challenges of work in remote data-scarce mountainous regions.

## 2.6. A multi-hazard framework

Drawing on the preceding analysis and focused on water, we propose a novel framework offering a comprehensive understanding of multi-hazards in a sustainable development context (Fig. 2.5). The framework foresees contributions from multiple academics from varied disciplines, non-governmental organisations (NGOs), national and local government bodies, impacted communities, and other end-users. From the outset, both quantitative physical science and qualitative social science methods are combined to generate actionable knowledge for multi-hazard mitigation and adaptation.

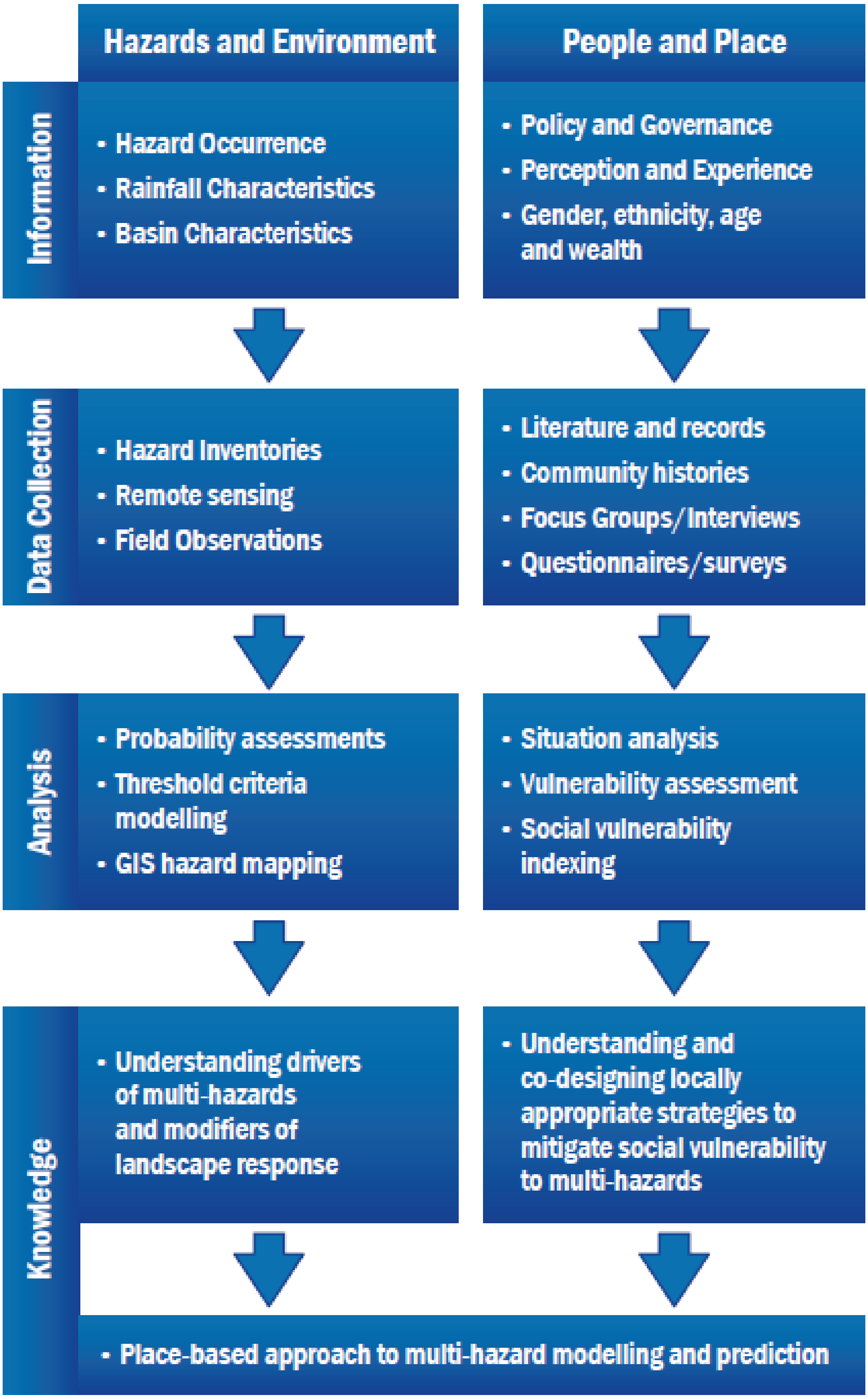


*Figure 2.5. A schematic overview of the proposed framework for understanding water-related multi-hazards in a sustainable development context. The bullet points show respectively the information required, methods of collection, methods of analysis, and the key knowledge points that lead to a place-based approach to multi-hazard modelling and prediction.*

The main pillars of the framework are the parallel themes of 'Hazards and Environment' and 'People and Place' that essentially encompass both quantitative and qualitative analytical methods of the driving forces of natural hazards and the risk that they pose. This relies on bringing together different data sources for analysis based on two key principles, namely understanding drivers of multi-hazards and modifiers of landscape response and understanding and co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards. Addressing these different principles in a systematic and coordinated way gives a place-based approach to multi-hazard modelling and prediction. We contend the utilisation of this framework would lead to multiple benefits for disaster relief agencies, governments and communities directly affected by multi-hazards.

### 2.6.1. Hazards and Environment

This pillar involves contextualising the hazards and environmental parameters within the physical setting based on the obtainable data, focused on investigating hydrologically induced landslides and flooding.

In LMICs there is a need for advancing technologies for data collection and processing, such as low-cost sensors, public domain datasets and new information communication technologies (ICTs) (Abdulwahid and Pradhan, 2017; Kucera et al., 2012; Zogheib et al., 2018). Our framework achieves this by developing and integrating information from various sources on multiple scales.

This pillar is broken down into 'information', 'collection' and 'analysis' sub-tasks using methods and techniques already widely used within the hazards literature (Allen et al., 2016; Dahal and Hasegawa, 2008).

Rainfall, the main driver of these systems, can be assessed according to various characteristics including magnitude, frequency, duration, and antecedent rainfall accumulation (Kansakar et al., 2004). For example, satellite rainfall products, such as the Tropical Rainfall Measuring Mission (TRMM) can be openly accessed and used to analyse broad scale rainfall distributions (Duncan and Biggs, 2012; Krakauer et al., 2013). Weather station data and rain gauges can be used to gather real-time high-resolution rainfall data which can be used to calibrate these products and provide detailed analysis (Overton, 2009; Prakash et al., 2016). Hydrological data from rivers can be gathered using field observations and river flow archives (where available) and can be used to assess past hydrological variability (Hannah et al., 2005). Field and satellite observations can be taken to analyse the river basin controls, such as elevation, slope, river density, and land cover. Time lapse analysis of these images can be used to investigate changes in the floodplain and slope vegetation and channel morphology. Hazard inventories based on satellite imagery and field mapping are used to account the timing and spatial extent of natural hazards within the system (Adhikari et al., 2010; Kirschbaum et al., 2015). The integration of this meteorological, hydrological, landscape, and hazard information enable an understanding of the sensitivity of water-related multi-hazards, providing the necessary support for hazard prediction and GIS-based modelling.

### 2.6.2. People and Place

We contend that people and place must be given equal importance to hazards and environment as shown in Figure 2.5. Specifically, the requirements and risk currencies of the impacted community and end-users must be considered from the outset and throughout the framework to ensure the outputs are useful, realistic, and sustainable.

Concurrent with ‘Hazards and Environment’, this pillar is also broken down into ‘information’, ‘collection’, and ‘analysis’ using existing methods (Preston et al., 2011).

At the national level, data should be obtained on disaster risk reduction policy, governance and societal structures from grey literature and government records. Community hazard resilience data can be accessed through qualitative methods such as situation analysis, which is the examination of a social situation, its elements, and their relations, to provide a state of situation awareness for decision makers and therefore greater adaptive capacity within the community (Santha and Sreedharan, 2010). These methods include vulnerability and capacity assessments, which involve a combination of focus groups and community/household level interviews, questionnaires, and surveys to collect information. Specific survey topics typically include contextual information about affected communities and the multiple hazards impacting them.

Social vulnerability refers to the social economic, and political factors that influence the degree to which individuals, communities, and systems are susceptible to, unable to cope with, and unable to adapt to the damaging effects of natural hazards. Some key elements that contribute to socio-economic vulnerability include power relations, human livelihoods, ownership of livestock and agricultural land, infrastructure provision, access to drinking water, communications, level of education, economy, and environment. These factors are important in supporting adaptation and coping strategies of different groups.

In essence, existing socioeconomic inequalities and lack of empowerment of disadvantaged groups results in uneven distribution of and exposure to disaster risks.

### 2.6.3. Knowledge

As noted above, the proposed framework aims to yield information of direct practical relevance with potential to support decision making for water-related multi-hazards based around two key principles, namely (1) understanding drivers of multi-hazards and modifiers of landscape response and (2) understanding and co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards. This involves first evidencing the co-occurrence of water-related multi-hazards then identifying hydrometeorological drivers and basin characteristics that modify those multi-hazards. This knowledge generation is the focus of Chapters 3 and 4. This can then be combined with social economic data to construct statistical, GIS-based models to yield predictive multi-hazard vulnerability. This will improve our understanding of the interactions of water-related multi-hazards, their driving forces, the factors that determine sensitivity of landscapes, and importantly the vulnerability of affected people. Prediction of multi-hazard scenarios is particularly key to this framework in an attempt to increase human preparedness and thus to increase potential resilience of people and infrastructure.

In this way we foresee the framework providing new insights into coping with the challenges of work in remote data-scarce regions of LMICs. This framework is designed to be used on multiple scales, adapting to the spatial and temporal resolution of the available data. Hence, hypotheses can be developed at a broad scale looking at large and long-term patterns from satellite data which can then be tested by telescoping into areas in which there has been detailed groundwork.

In addition, the proposed framework copes with the communication challenges and supports a continual dialogue with stakeholders. Disaster risk reduction and progress in sustainable development of vulnerable communities can only be achieved by engaging stakeholders and initiating a response to actionable knowledge. Therefore, effective communication between science and stakeholders is vital to this framework (Buytaert et al., 2014). The SFDRR stated the importance of ‘society engagement’ and the ‘voluntary work of citizens’ (UNISDR, 2015). This framework offers many opportunities for participatory approaches to knowledge generation. Leveraging new technologies such as low-cost sensors in combination with smartphones and internet, such approaches may allow community members to play pivotal roles in leading the measurement of environmental parameters, such as precipitation, river water levels, and soil moisture. The participation of non-professional scientists in data collection, interpretation, and analysis could increase the amount and quality of available data, whilst also engaging affected communities and promoting a better response to actionable knowledge (Paul et al., 2018). It also provides tools for local communities to address decisions related to disaster risk reduction in more socially equitable ways. This tackles the failures of existing ‘top down’ governance models, common to LMICs, that depend on external interventions and are blind to the needs of marginal communities.

### 2.6.4. Benefits of this framework

We argue the utilisation of this framework has considerable potential to further understandings of hydrologically driven multi-hazard environments, most clearly by providing novel insight into how social vulnerability to these multi-hazards occurs within place. Thus, we envisage that by applying this framework community awareness of the interconnections between hazards will be boosted, offering a platform for structuring co-generation and sharing of knowledge, data, and resources on locally specific multi-hazards. Co-generation of knowledge facilitates the integration of diverse perspectives, knowledge systems, and methods, leading to a more holistic understanding of multi-hazard scenarios.

The framework could be further enhanced through new data gathering opportunities via low cost sensor applications currently under development in hydrology, that seek to generate actionable knowledge for improving/refining multi-hazard forecasting capabilities (Mao et al., 2018). Such an approach has the potential to empower communities to respond more effectively to multi-hazards, reducing localised disaster risk, increasing community resilience, and promoting sustainable development goals.

## 2.7. Conclusion

This chapter proposes a new framework for investigating water-related multi-hazards through leveraging and synthesising existing methods to address the challenges and gaps identified to date. More specifically, building on a comprehensive bibliometric analysis of the multi-hazard literature, the study provides a broad overview and comparison of approaches currently used by the research community to evaluate and model different types of hazard interrelations. This preliminary review, identifying main gaps and challenges on current approaches, presents the knowledge base for the design of the novel framework for multi-hazards appraisal able to address geographically specific key considerations including available and accessible data, community variability, and cross-sectoral collaborations.

Future work will involve the utilisation of the framework to investigate the patterns and natural and anthropogenic controls of hydrologically induced landslides and flooding at a case study level. This will be the focus of Chapters 3 and 4. This information will be used to generate regional models and predictions to support the design and implementation of preparedness plans. This progression in our knowledge and understanding can be adapted to cover a broader range of multi-hazard scenarios and a wider geographic perspective.

# Chapter 3 - Water-related multi-hazards in Nepal: exploring space-time patterns in co-occurrence of landslides and flooding

## 3.1. Abstract

Nepal is a hotspot for natural hazards, including hydrologically induced landslides and flooding. We apply the framework developed in Chapter 2 to structure our broad scale analysis of the occurrence and potential co-occurrence of these hazards. The framework was developed from analysis of the multi-hazard literature and critical evaluation of existing approaches; and it offers guidance on how to understand water-related multi-hazards in a sustainable development context by synthesising natural and social science approaches. To test the ‘Hazards and Environment’ pillar of the framework, we collected data on flood and landslide occurrence, monsoon rainfall and basin characteristics - from hazard inventories and remote sensing - and then analysed using geographical information systems (GIS). In structuring our analysis, we divide Nepal into nine geographical zones based on drainage basin and physiography. My analysis shows that the seasonal occurrence of landslides and flooding varies spatially across the nine zones and there is evidence of co-occurrence. We found that the magnitude and timing of the monsoon precipitation varies spatially, and this appears to be a key driver of these multi-hazards. Other possible causative factors were investigated, notably catchment properties (slope, river density, river gradient, land cover, and geology), were found to modify both the rainfall and the hazard occurrence. This broad scale analysis is novel in identifying co-occurrence and

important for describing the overarching interactions and processes, which will be explored in Chapter 4 by zooming in on the rainfall characteristics (rainfall magnitude, frequency, duration, antecedence) and looking at other driving factors, such as road construction, geology, and atmospheric circulation. This research will provide a first perspective and understanding of water-related multi-hazards in Nepal.

## 3.2. Introduction

Hydrologically induced landslides and floods are among the most destructive natural hazards globally (Ávila et al., 2016). In mountainous regions, where these landslides and floods are often interrelated, research on the two hazards often falls separately. There are numerous publications on landslides in which flooding does not feature (e.g., Froude and Petley, 2018; Kirschbaum et al., 2020; Muñoz-Torrero Manchado et al., 2021) and many publications on surface water processes, which do not mention mass movements (e.g., Delalay et al., 2020; Huggel et al., 2020; Kundzewicz et al., 2017; Shrestha et al., 2021). There is a need for a multi-hazard approach as stated in the Sendai framework of Disaster Risk Reduction (SFDRR) (UNISDR, 2015), especially in a changing climate (Gautam, 2017).

Landslides and flooding are generally associated with a trigger, such as extreme rainfall (Malamud et al., 2004). Current research on climate change projects a future increase in the global frequency and intensity of heavy rainfall events. These changes could result in a higher likelihood of these multi-hazards, particularly in steep mountain environments where geomorphology plays a pivotal role (Kirschbaum et al., 2015). In addition, it is of particular importance to study the interactions or co-occurrence between landslides and flooding among the suite of multi-hazards because these hydrological processes overlap and interact. Furthermore, there is potential to underestimate risk when analysed separately.

There is less research on multi-hazards in lower- and middle-income countries (LMICs) and remote environments due to data scarcity and limited accessibility (Docherty et al., 2020). Nepal, one of the world's least developed countries, is exposed to a range of water-related multi-hazards, namely floods and hydrologically induced landslides (Aksha et al., 2018; Nadim et al., 2006; Petley et al., 2007). The majority of these multi-hazards are linked to the occurrence of the summer monsoon, June to September (Stanley et al., 2020). There have been a number of studies on temporal and spatial changes to monsoon precipitation in Nepal (Bohlinger and Sorteberg, 2018; Talchabhadel et al., 2018). Kansakar et al. (2004) provided a large-scale perspective upon the nature of precipitation regimes across Nepal and found spatial variation in the timing and intensity of the summer monsoon. This has implications for region-specific risks of landslides and flooding that have not yet been looked at in combination.

In hazardous environments, the nature of the landscape affects the occurrence of hazards (Pearson et al., 2022). It is known that the landscape of Nepal varies spatially in relation to the relief, river attributes, land cover, and geology. This, in turn, must have impacts on the movement of the South Asian Monsoon and the occurrence of multi-hazards (ADPC et al., 2010). Water-related multi-hazards are known to cause significant damages to infrastructure, such as bridges, railways, and road systems (Liu et al., 2018). Building of these anthropogenic systems disturbs the natural environment interactions and has been found to be a major cause of hazards, in addition to the hydrometeorology (Muñoz-Torrero Manchado et al., 2021). Therefore, catchment properties, including anthropogenic factors, modify rainfall triggers and effect the processes leading to hazards.

Through bibliometric analysis in Chapter 2, it is known that landslides and floods frequently co-occur in the literature. Yet understanding of their interactions, hydrometeorological drivers and landscape controls remain poorly conceptualised; this was recognised as a clear research gap. It was also found that there is a geographical bias, with less research carried out in less economically developed countries and remote environments, thus making Nepal an appropriate case study. A framework was developed for understanding water-related multi-hazards in a sustainable development context. The framework comprises two main pillars, ‘Hazards and Environment’ and ‘People and Place’, guiding the data collection, analysis, and interpretation to form a place-based approach to multi-hazard modelling and prediction. This chapter will follow the ‘Hazards and Environment’ pillar of the framework to further our knowledge on these hazards from a natural science perspective.

The aim of this chapter is to understand the broad scale spatial variation of landslides and floods in Nepal and how they co-occur. This will be achieved according to three key objectives: (1) to explore the spatial variation and potential co-occurrence of landslides and flooding, (2) to assess seasonal precipitation as a potential driver of the space-time patterns of multi-hazards, and (3) to consider catchment properties as a modifier of the drivers and hazard interactions. This research has implication for real world applications - to increase community resilience, reduce disaster risk, and make progress towards sustainable development.

## 3.3. Physiographic, hydrological, and social background to Nepal

Nepal is a landlocked country in South Asia, bordering India in the south, west, and east, and China in the north. Nepal's physiographic zones exhibit extreme differences in elevation and slope. The southern floodplains of the Terai are at a very low elevation (57m above sea level) with the majority of slopes below 5 degrees (ADPC et al., 2010). The elevation and slope increase abruptly moving north creating the rough hill terrain and then into the highly elevated, steep slopes of the Himalayan Mountain belt where Mount Everest (8848m) stands as the world's highest peak (Aksha et al., 2018). The three major drainage basins (Karnali, Gandaki and Koshi), divide the country into approximately equal areas perpendicular to these physiographic zones (Kansakar et al., 2004).

Nepal is classified as a low- and middle- income country (LMIC), with a human development index (HDI) (a measurement of life expectancy and standard of living) rank of 143/189 countries (GoN, 2017a). The country has high exposure to natural hazards and is regularly classified as high risk on disaster and climate vulnerability indices (HDR, 2019). According to Government of Nepal (GoN) data, up to 80% of the population is at risk of being adversely affected by natural hazards (GoN, 2017b). In 2017/18, for example, 968 people were killed, and an estimated 27,265 families were affected by hazards (GoN, 2019: 4). After earthquakes, landslides and flooding represent the chief hazards, often resulting in considerable damage to infrastructure and livelihoods.

The summer monsoon is responsible for the majority of these hazards. It is characterised by intense rainfall during the four months from June to September which contributes to 80% of the annual rainfall (Kansakar et al., 2004). Heavy rainfall is responsible for the majority of landslides in Nepal, and floods can often induce landslides by the scouring of riverbanks during high water flows (Delalay et al., 2020; Monsieurs et al., 2018). River floods generally occur as inundations of large areas due to the overflowing of riverbanks. These cause extensive damages to people but can usually be predicted (Kundzewicz et al., 2017). As rainfall is the primary trigger for water-related multi-hazards, there is a need for accurate determination of the rainfall regimes across the country and how these are influenced by catchment properties.

## 3.4. Data and methods

### 3.4.1. Spatial structure for analysis of hazard co-occurrence

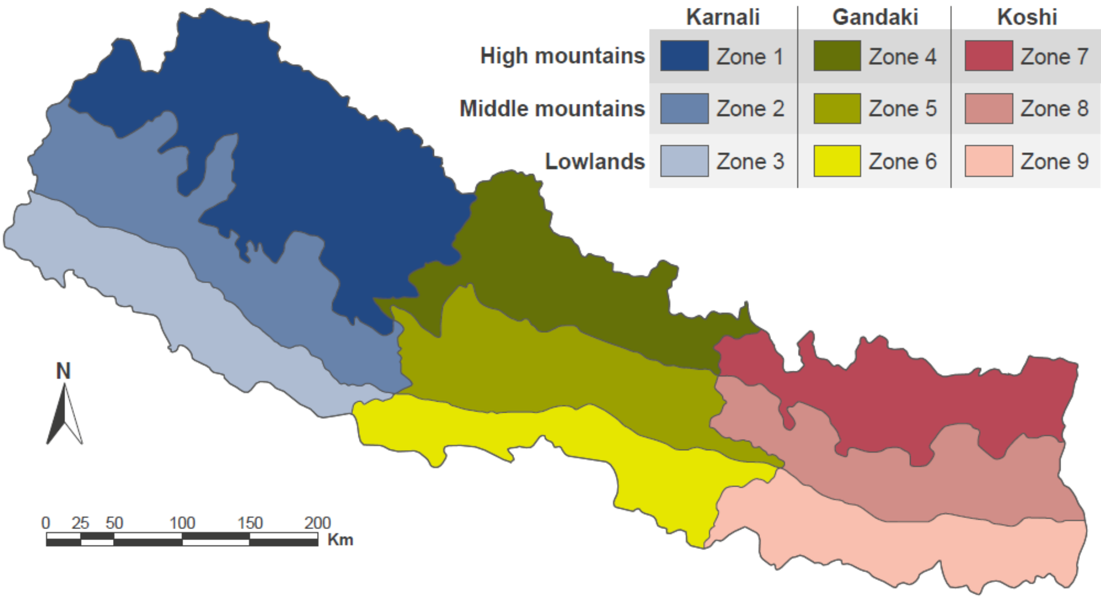


*Figure 3.1. Nepal divided by drainage basin and physiography into nine zones.*

In this analysis, we have used drainage basin and physiographic region to divide the country into nine zones using GIS mapping techniques (Fig 3.1). The reason for this division is that historically these have been used as the nine natural regions of Nepal. They are divided in this way in the hydrological atlas of Nepal (ICIMOD, 1996) and used as such in a number of publications including Kansakar et al. (2004). Physiographic zones were derived from Dhital (2015) which is a modification derived from the classification in Hagen (1969). These were then merged with the river basins falling within the outer boundary of Nepal. The three physiographic areas were then intersected by the three major drainage basins to delineate the nine basic zones. The main basin divisions have been delineated with Arc Hydro package tools for ArcGIS version 10.7 (ESRI, 2018) using the Shuttle Radar Topography Mission (SRTM) Digital

Elevation Model (DEM) of 90m. The southern margins of these basins were defined by smaller basins that extend outside the limits of the Nepal boundary. These southern partial basins were aggregated to the major basins to obtain the final three main basin areas. While previous geographic research on Nepal has used administrative boundaries to structure data analysis (Froude and Petley, 2018), we believe that our strategy will provide a more holistic understanding of the multi-hazard interrelationship.

The three physiographic zones are the Lowlands, Middle Mountains, and the High Mountains (south to north) (Fig. 3.1).

- The Lowlands corresponds to the Terai, Siwaliks and Dun Valleys.
- The Middle Mountains corresponds to the Maharabat Range and Midlands.
- The High Mountains corresponds to the Fore, Inner and Greater Himalayas, the Tibetan Marginal Range, and the Tibetan Plateau.

These areas are subdivided by three major river basins: the Karnali, Gandaki, and Koshi (west to east) (Fig. 3.1).

- The Karnali area includes the Karnali, Mahakali, Babai, and West Rapti.
- The Gandaki area includes the Gandaki, and Bagmati.
- The Koshi area includes the Koshi, Kamala, and Kankai.

The nine zones, as shown in Figure 3.1, are as follows:

- Zone 1 = The High Mountains of the Karnali
- Zone 2 = The Middle Mountains of the Karnali
- Zone 3 = The Lowlands of the Karnali
- Zone 4 = The High Mountains of the Gandaki

- Zone 5 = The Middle Mountains of the Gandaki
- Zone 6 = The Lowlands of the Gandaki
- Zone 7 = The High Mountains of the Koshi
- Zone 8 = The Middle Mountains of the Koshi
- Zone 9 = The Lowlands of the Koshi

### 3.4.2. Data sets

This study will use the 'Hazards and Environment' pillar of the multi-hazard framework outlined in Chapter 2 (Fig. 3.2) to understand the hydrometeorological drivers and landscape controls of landslides and floods in a broad scale analysis of Nepal.

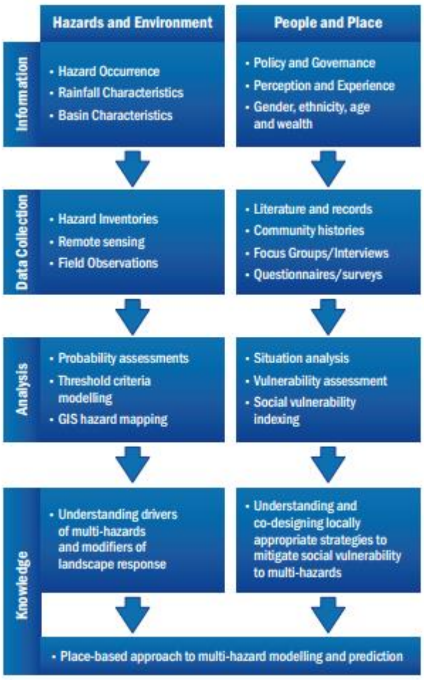


*Figure 3.2. A framework for understanding water-related multi-hazards in a sustainable development context (Docherty et al., 2020).*

As stated in this pillar, the information required includes hazard occurrence, rainfall characteristics, and landscape characteristics. In this case study, these data will be obtained using hazard inventories and remote sensing. This understanding could be used for probability assessments, rainfall threshold criteria modelling, and GIS hazard mapping. This will further our understanding of water-related multi-hazards and the modifiers of landscape response. When combined with work on people and place, this will provide the knowledge for a place-based approach to multi-hazard modelling and prediction.

*Hazard inventory data*

The hazard inventory used in this study is the Disaster Inventory System (DesInventar). There are several alternative hazard databases that could be used for this analysis which have differing strengths and weaknesses. Emergency Events Database (EM-DAT) is one of the most widely used global databases that compiles data on global disasters since 1900. However, it relies more on media resources rather than national government records, which can lead to inconsistent reporting across events and countries (Panwar and Sen, 2020).

DesInventar is an open-source hazard inventory for observing natural disasters that have caused damage and loss (UNDRR, 2022). The data are compiled from government and aid agency reports, academic papers, newspapers, and other media sources. Any recorded disaster that has caused direct or indirect damage is included in the database allowing assessment of both small and large events. This granularity makes it more applicable for broad scale analysis.

The DesInventar database for Nepal started in 1971 and ends in 2013 covering earthquakes, floods, landslides, drought, and epidemics. In this study, the DesInventar database was used to observe a 20-year time period for landslides and floods (1993 - 2013). This time period was chosen given uncertainties in recording biases and completeness during the early part of the record and the database only recording up to 2013. Although there are no notable events in this time period, there is good variation in the number of multi-hazards with some years in which there are many hazards and others when there are few.

*Hydrometeorological data: rainfall*

Rainfall data was derived from the European Centre for Medium Range Weather Forecasts (ECMWF) atmospheric reanalysis version 5 (ERA5) gridded precipitation climate datasets, part of the ERA5 2D surface analysis products derived from the 4D-Var data assimilation in CY41R2 of ECMWF's Integrated Forecast System. The data sets cover the period 1979 to present, although we have only used data between 1993 and 2013 to correspond to the hazard data. The cell size resolution is 30km (0.25° x 0.25°) and consists of 273 polygons within the Nepal boundary corresponding to 273 unique locations. Satellite data was used because there was no weather station data available for the purpose of the analysis.

There were a number of other satellite rainfall products available, such as Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Measurements (GPM), Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE), Climate Hazards Group InfraRed Precipitation with station (CHIRPS), and Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (IMERG). The resolution and time range of these datasets are listed in Table 3.1 showing that ERA5, TRMM and APHRODITE have a resolution of 0.25° x 0.25°, GPM has a resolution of 0.1° x 0.1°, and CHIRPS has the finest resolution of 0.05° x 0.05°. Despite ERA5 having a coarser resolution, it was chosen because it covers a long period and has previously shown to be able to capture long-term trends and help with identifying climate features (Hamm et al., 2020). In a study comparing various satellite rainfall products including APHRODITE, TRMM, and ERA5 it was proved that ERA5 provided the most reliable estimates (Kanda et al., 2020).

*Table 3.1. The resolution and time period of a range of satellite rainfall products.*

| **Rainfall Dataset** | **Resolution** | **Data period** |
|---|---|---|
| ERA5 | 0.25° x 0.25° | 1940 - present |
| TRMM | 0.25° x 0.25° | 1997 - 2015 |
| GPM | 0.1° x 0.1° | 2014 - Present |
| APHRODITE | 0.25° x 0.25° | 1966 - Present |
| CHIRPS | 0.05° x 0.05° | 1988 - Present |
| IMERG | 0.1° x 0.1° | 2014 - Present |

*Geomorphological data*

River network data from 2015 was obtained from the Government of Nepal (GoN) Department of Hydrology and Meteorology (DHM) (DHM, 2015). All hydro-topographic analyses (slope and river gradient) were based on the SRTM obtained at 90-meter (3 arc-second) resolution.

*Land cover data*

The land cover data was created through the National Land Cover Monitoring System (NLCMS) and sourced from the International Centre for Integrated Mountain Development (ICIMOD) (ICIMOD, 2022). It covers the whole of Nepal and is from 2019. There are eleven land cover classes, namely water, glacier, snow, forest, riverbed, built-up, cropland, bare soil, bare rock, grassland, and other woodland. There have been significant landcover changes over the past 20 years therefore there are implications of using a single land cover map as it doesn't show the changing pressures on the landscape throughout our time period. This is considered later in the chapter.

Geological data

Geological data was obtained from the Nepal Hazard Risk Assessment (NHRA) from the Asian Disaster Preparedness centre (ADPC et al., 2010). The map and table presented show the geological units and their susceptibility to multi-hazards.

### 3.4.3. Data analysis

The seasonality of multi-hazard occurrence was determined by examining the cumulative landslides and floods in each zone by month. This obtained information on the space-time patterns of co-occurrence of landslides and flooding.

Landslide and flood data were extracted from the DesInventar database for the period 1993-2013. Each hazard occurrence was assigned to the month (June – September) and zone in which it occurred, and the total flood and landslide hazards in each month and zone were summed up.

For there to be co-occurrence of landslides and flooding, the number of both landslides and floods in a certain zone and month must be relatively high compared to the expected number of hazards. The expected number of hazards can be estimated by assuming that hazards are uniformly distributed across Nepal and occur uniformly over the months June – September. Therefore, the expected number of landslides $E_{\text{landslides}}$ is given by the total number of landslides in Nepal divided by 4 (number of months) then divided by 9 (number of zones) – i.e.

$$E_{\text{landslides}} = \frac{\sum_{1993}^{2013} \text{Landslides}}{N_{\text{months}} N_{\text{zones}}}$$

The expected number of floods $E_{\text{floods}}$ is defined in a similar way. For the obtained data, we find that $E_{\text{landslides}} = 68$ and $E_{\text{floods}} = 54$ – i.e. on average, we expect there to be 68 landslides and 54 floods in each zone in each month.

We define there to have been high co-occurrence if *both* the number of floods and number of landslides in a given zone and month are larger than their expected value. Therefore, if there are more than 68 landslides *and* more than 54 floods in a certain zone and month, then we categorise this as a high co-occurrence event.

The ERA5 grid data was overlain with the nine zones in order to show which ERA5 grid cells fell into each zone. This gave us the relative area percent of each grid cell within each zone which was used to calculate the mean daily precipitation values (mm). The mean, maximum and minimum rainfall were calculated for each of the nine zones for each of the monsoon months. This was used to observe broad scale rainfall patterns across Nepal over the 20-year period.

The geomorphology and landscape characteristics (slope, river density, river gradient, and land cover) were then derived from GIS analysis and assessed for the nine zones using the hydrological toolbox in ArcGIS. Zonal statistics were performed to establish aggregated values within each study zone. The percentage land cover was also calculated for each of the nine zones and the results were presented in pie charts.

In addition, some statistical tests were performed to investigate changes in the catchment characteristics in relation to the hazards. A non-parametric statistical test and Analysis of Similarities (ANOSIM) were performed along with Principal

Component Analysis (PCA). Boxplots were created showing the variation in basin metrics and hazards between the mountainous zones.

## 3.5. Results

The purpose of this study was to understand the broad scale variation of water-related multi-hazards in Nepal. To address this we have presented the landslide and flood occurrence (Fig. 3.3) to explore the space-time patterns and possible co-occurrence of landslides and floods in section 3.5.1. This has then been compared to the seasonal precipitation for each of the nine zones to assess precipitation as a potential driver in section 3.5.2. Finally, I present the mean slope, river density, river gradient (Fig. 3.4) and percentage distribution of land cover (Fig. 3.5) in section 3.5.3 to consider the catchment properties as a modifier of the drivers and hazard interactions.

### 3.5.1. Space-time co-occurrence of water-related multi-hazards

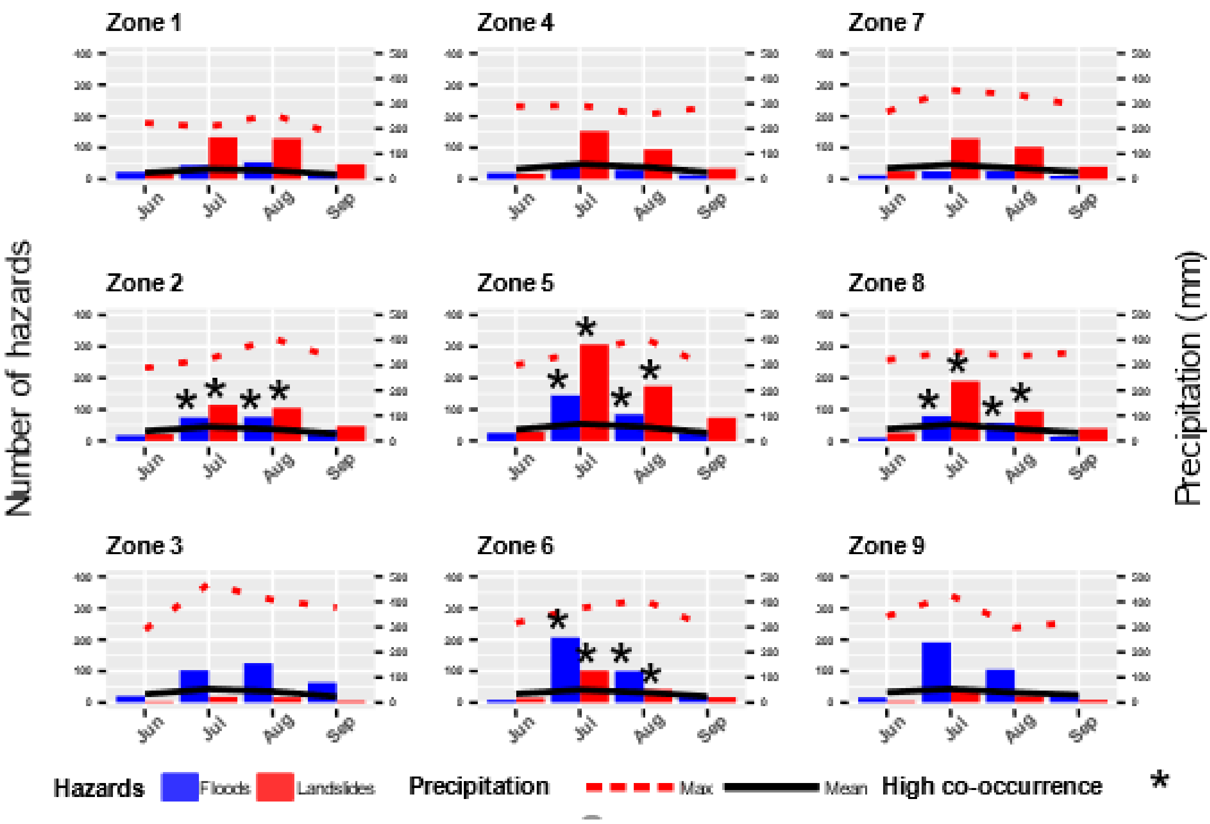


*Figure 3.3. Spatial distribution of the cumulative landslide and floods between 1993 and 2013 throughout the monsoon season (June – September) and the maximum, and mean seasonal precipitation derived from ERA5 daily values. Black asterisks above the columns indicate high levels of co-occurrence.*

There is space-time variation in the co-occurrence of water-related multi-hazards across Nepal seen in Figure 3.3. Floods and landslides co-occur in all of the nine zones at varying levels. High levels of co-occurrence exist where both numbers of floods and landslides are above their relative metrics, for landslides this is 68 and for floods the number is 54. There are low levels of co-occurrence in June and September in all of the zones. There is high co-occurrence in July and August in the Middle Mountains and in the Lowlands of the central Gandaki river basin (Zones 2, 5, 6, and 8). This is indicated in Figure 3.3 by asterisks above the columns.

In the Lowlands (Zones 3, 6, and 9) there are a high number of floods, more than 100 events per month in July and August in each zone. Floods peak in July in Zones 6 and 9 with 207 and 191 events respectively and fall rapidly in August to 100 and 105. In Zone 3, the frequency of flood events is lower with a peak of 125 events in August. Levels of co-occurrence are low in Zones 3 and 9 where landslide numbers peak at less than 50, below the co-occurrence metric. Levels of co-occurrence are high in the Lowlands of the central Gandaki basin (Zone 6) particularly in July when flood numbers are 207 and landslide numbers are 102.

The Middle Mountains (Zones 2, 5, and 8) have the highest number of recorded landslide disasters with a peak of 307 in July, in Zone 5. The frequency of flood events is also high with a peak of 145 events in July, in Zone 5. Therefore, we have co-occurrence of hazards in July and August in this physiographic region. Landslides and floods peak in July in Zone 5 and 8, then fall in August. Zone 5 has the greatest decrease in landslides, from 307 in July to 174 in August, and Zone 8 decreases from 190 to 95. Floods are comparatively lower than landslides in Zones 5 and 8, but still see a marked drop in August. Zone 2, on the other hand, has landslides peaking in

July with 114 events and remaining high in August with 105 events. There are more landslides than floods in this zone, but floods are high in July with 74 and peak in August with 76.

In the High Mountains, landslide numbers are relatively high with peaks of 133, 152, and 129 in July in Zones 1, 4, and 7 respectively. The number of flood events per month is less than 54 across all zones meaning that co-occurrence is low in this region.

In terms of east to west variation, the western Karnali river basin (Zones 1, 2, and 3) has different patterns from the central Gandaki (Zones 4, 5, and 6) and eastern Koshi (Zones 7, 8, and 9). The Middle Mountains of the Koshi and Gandaki (Zones 5 and 8), are a hotspot for landslides in July unlike the Middle Mountains of the Karnali (Zone 2). Both hazards are considerably lower in the Karnali than in the Koshi and Gandaki and they peak later in the season, in August rather than July.

Co-occurrence of landslides and flooding is highest across the Middle Mountains (Zones 2, 5 and 8) and in the Lowlands of the Gandaki basin (Zone 6). These are hotspot regions for both types of hazards.

These interpretations are useful for understanding the way in which the occurrence and co-occurrence of water-related multi-hazards varies spatially across the country. This must be related to potential drivers such as seasonal precipitation, and possible modifiers such as catchment properties which will be explored in the following sections.

### 3.5.2. Seasonal precipitation as a potential driver of hazard co-occurrence

The seasonal precipitation varies spatially as seen in Figure 3.3. The minimum daily precipitation is very low in all zones where rain is often 0 mm (not plotted) and the mean precipitation follows a similar pattern in each zone varying between 23 mm and 67 mm. Maximum precipitation is highest in the Lowlands (Zones 3, 6, and 9) with the highest maximum precipitation in Zone 3. There is high variation in this zone with the maximum precipitation low in June 290 mm then increasing sharply to peak of 471 mm in July then gradually decreasing to 408 mm in August and 327 mm in September.

In contrast, the lowest maximum rainfall is in July in the High Mountains of the Karnali basin (Zone 1) where it only reaches 208 mm in August. Precipitation is higher in the other High Mountain zones (Zones 4 and 7) where there is some variation in the maximum precipitation throughout the monsoon with a peak of 293 mm in July in the High Mountains of the Gandaki (Zone 4) and a peak of 353 mm in the High Mountains of the Koshi (Zone 7).

There is variation in the onset and cessation of the monsoon from east to west. In the eastern Koshi basin (Zones 7, 8 and 9) the maximum monthly precipitation peaks in July in all three zones. In Zone 7, there is a rapid monsoon onset and then a gradual cessation until September when the maximum precipitation is 292 mm. The precipitation in the Middle Mountains of the Koshi basin (Zone 8) is consistently high with a peak of 353 mm in July. Maximum rainfall varies across a wide range in Zone 9 from 343 mm of maximum precipitation in June, increasing to a high peak of 427 mm in July followed by a very sharp decrease to August to 298 mm then a slight increase in September to 321 mm.

The Lowlands and Middle Mountains of the central Gandaki basin (Zones 5 and 6) follow the same shape with a gradual onset from June to a peak of 408 mm in August followed by a rapid cessation to September when it is 298 mm. Further west in the Karnali basin (Zone 2) maximum precipitation is low in June with 290 mm, has a rapid onset into July to 324 mm, peaks in August at 408 mm, and then decreases in September to 327 mm. This is evidence of the monsoon arriving earlier in the east and progressing westward.

In summary, there is a large variation in the maximum precipitation and seasonal distribution precipitation in each zone and there is evidence of the monsoon arriving earlier in the east and progressing westward. This may be a driving force of landslides and flooding although other factors, such as landscape characteristics, must also be considered.

### 3.5.3. Landscape characteristics as a possible modifier of rainfall and hazard co-occurrence

*Slope, river gradient, and river density*

The landscape characteristics of Nepal vary greatly from south to north. Figure 3.4 shows the landscape metrics: mean slope, mean river gradient, and river density. A map of Nepal showing the slope and river network is provided in Figure 3.5.

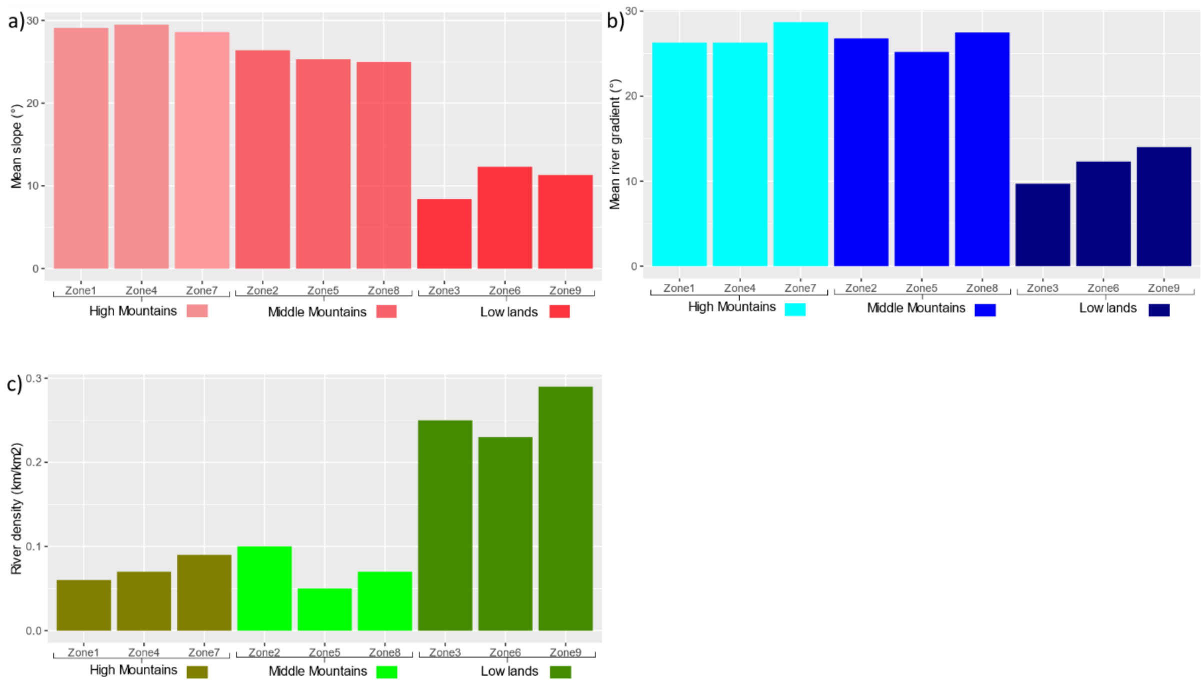


*Figure 3.4. Variation in basin metrics of a) mean slope, b) mean river gradient, and c) river density across the nine zones.*

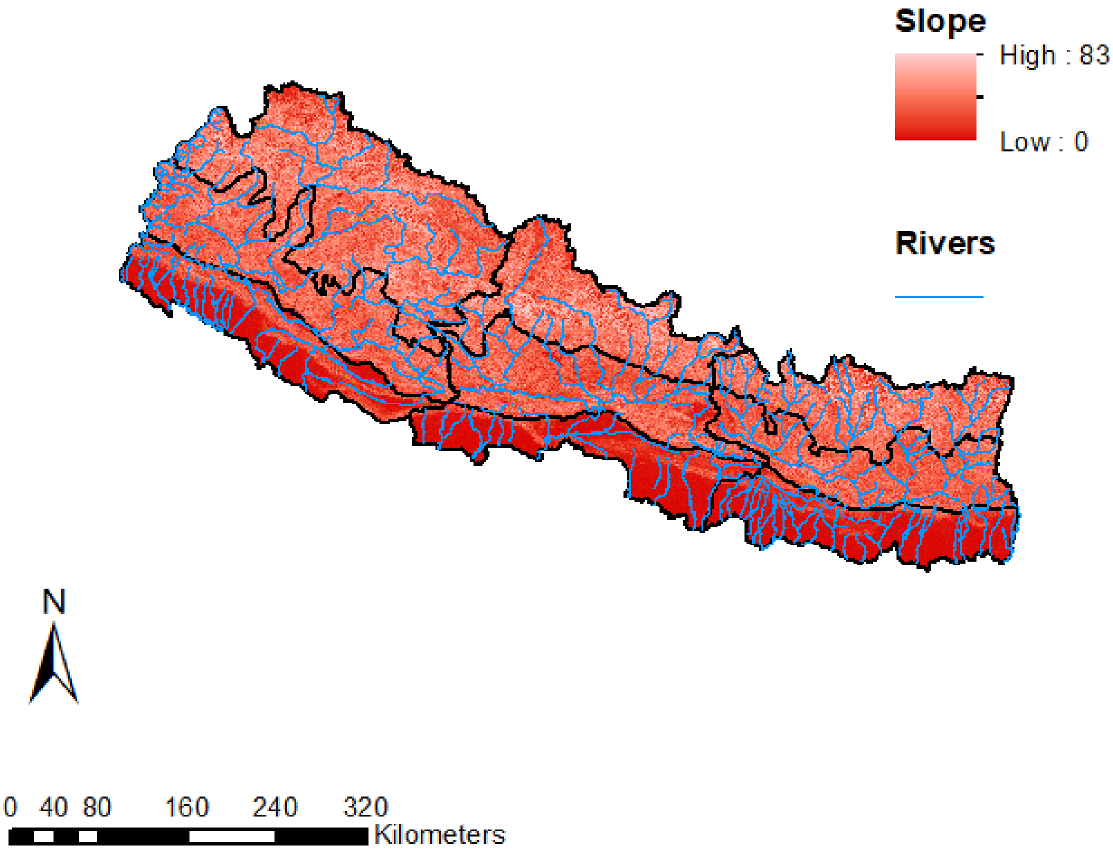


*Figure 3.5. Map of Nepal showing the variation in slope and river network.*

There is variation in the mean slope throughout Nepal. This is shown in panel a of Figure 3.4 and the map in Figure 3.5. The Lowlands (Zones 3, 6, and 9) are at a very low elevation and have the lowest mean slope values. There is variation in the mean slope throughout the Lowlands; Zone 3 has the lowest slope with 8.4°, Zone 9 has a higher slope of 11.3° and Zone 6 has the highest with 12.3°. The Middle Mountains (Zones 2, 5, and 8) have much higher slopes. These slopes do not vary greatly from east to west with the highest 26.4° in Zone 2, 25.3° in Zone 5, and 25° in Zone 8. Slope is highest in the High Mountains (Zones 1, 4, and 7) and vary within 1° of each other. Zone 1 has slopes of 29.1°, Zone 4 has slopes of 29.5° and Zone 7 has slopes of 28.6°. The slope increases from north to south and does not vary much from east to west in the High Mountains or Middle Mountains. There is a greater variation in slope in the Lowlands with the highest slopes in the Gandaki basin, a hotspot for co-occurrence of hazards.

River gradient follows a similar trend as the slope, with the lowest river gradient in the Lowlands (Zones 3, 6, and 9) where values are 9.7°, 12.3°, and 14° respectively. This can be seen in panel b of Figure 3.4. The slopes are steeper in the High Mountains (Zones 1, 4, and 7) and the Middle Mountains (Zones 2, 5, and 8). There is very little variation between these physiographic regions with the mean river gradient ranging from 25.2° in Zone 5 to 28.7° in Zone 7.

The river density increases from north to south with the highest values in the Lowlands (Zones 3, 6, and 9) where the values are 0.25, 0.23 and 0.29 km/ $km^2$ respectively. This can be seen in panel c of Figure 3.4. It then decreases to values between 0.05 and 0.10 km/ $km^2$ in the High Mountains (Zones 1, 4, and 7) and the Middle Mountains (Zones 2, 5, and 8).

In summary, slope and river gradient increase moving northwards and river density decreases. There is little change from east to west in any of these parameters.

*Land cover*

Land cover varies across Nepal and has changed significantly over time. Figure 3.6 shows the land cover of Nepal from ICIMOD in 2019. The land is categorised as water, glacier, snow, forest, riverbed, built-up area, cropland, bare soil, bare rock, grassland, and other wooded land (OWL).

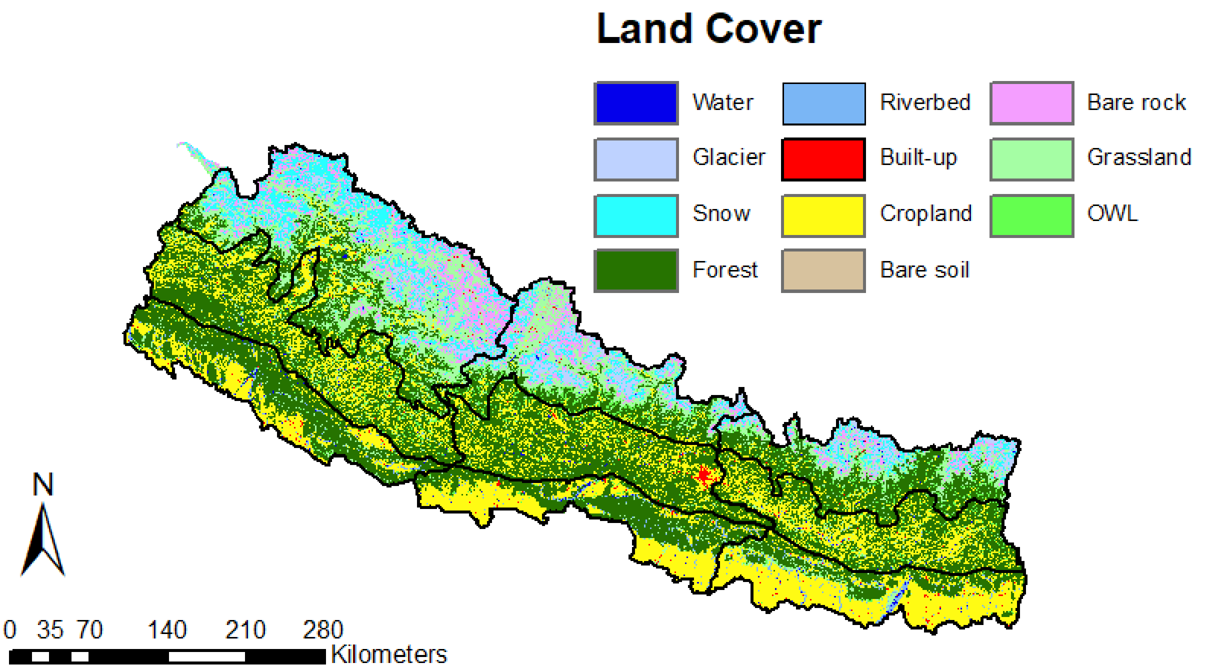


*Figure 3.6. Land cover from ICIMOD 2019 showing the areas covered by water, glacier, snow, forest, riverbed, built-up area, cropland, bare soil, bare rock, grassland, and other wooded land (OWL).*

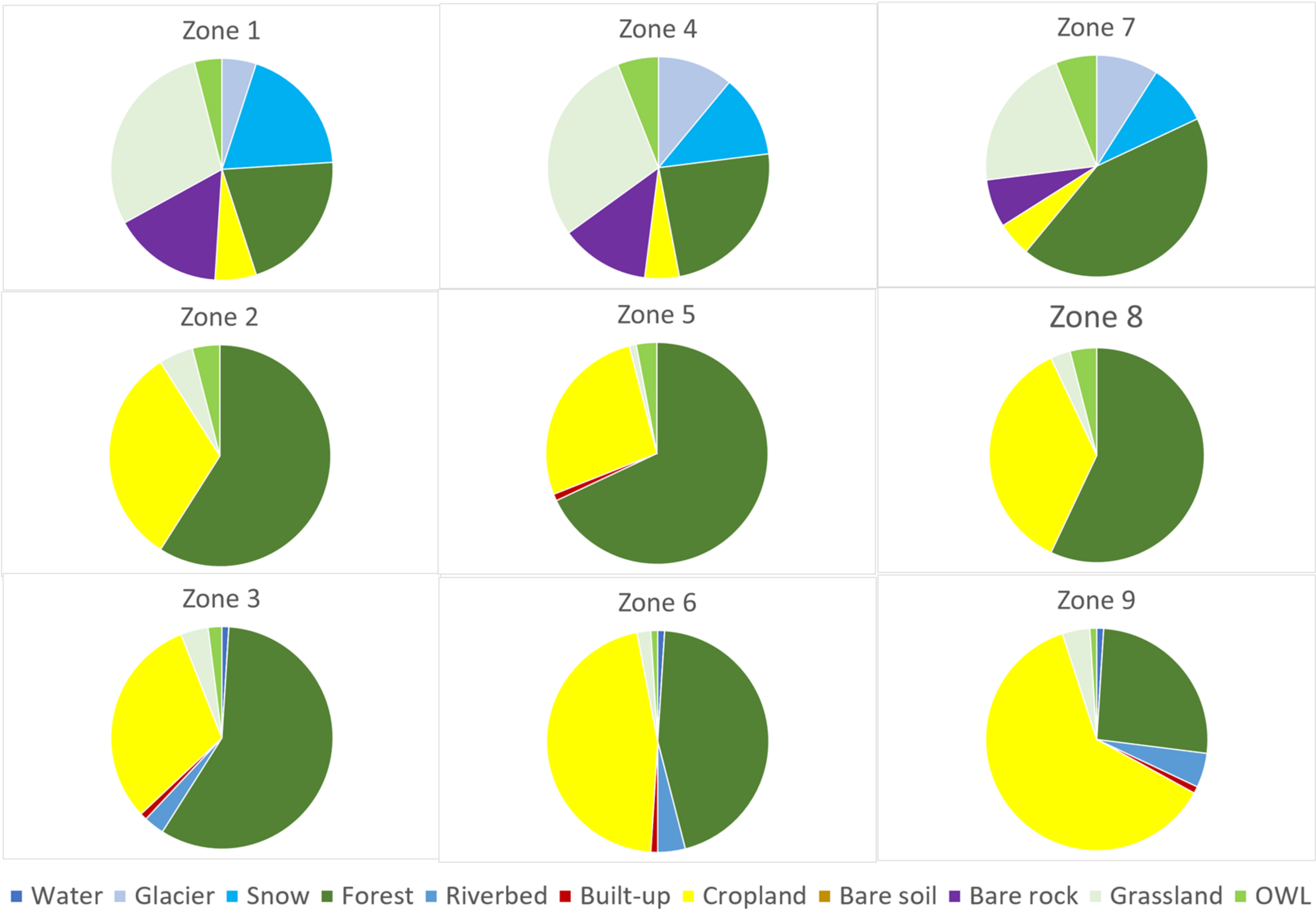


*Figure 3.7. Percentage landcover by zone based on data from ICIMOD 2019.*

Land cover varies across Nepal (Fig. 3.7). Forest covers the highest percentage of land across the Middle Mountains (Zones 2, 5, and 8) as well as Zones 3 and 7. The percentage of forest in the Middle Mountains of the Gandaki (Zone 5) is 68%. Cropland dominates the Lowlands of the Gandaki and Koshi basins (Zones 6 and 9) where the land is flat and fertile. The Lowlands of the Koshi (Zone 9) is covered by 62% cropland then the percentage of cropland decreases on moving north with 36% cropland in the Middle Mountains of the Koshi (Zone 8) and only 5% of cropland in the High Mountains of the Koshi (Zone 7). The High Mountains (Zones 1, 4, and 7) have very low agricultural potential with a high percentage of bare rock with no soil or vegetation and water body, which is made up of snow and glacier. For example, the High Mountains of the Koshi (Zone 1) has 19% snow and 5% glacier.

*Geology*

In Table 4.2 and Figure 4.21, taken from ADPC et al., 2010, the geology of Nepal is split into five landslide susceptibility classes low, moderate, medium, high, and very high.

The geology indicates that there is a very high susceptibility to multi-hazards in the Lowlands where there is predominantly fluvial sediments, alluvium, boulders, gravels, sands, and clays. The Middle Mountains vary between high and medium with some parts in the west having moderate susceptibility linked to the presence of sandstones, limestones, and shales. The High Mountain has a very mixed geology so although it is mainly moderate there are some patches of each of low, medium, high, and very high susceptibility.

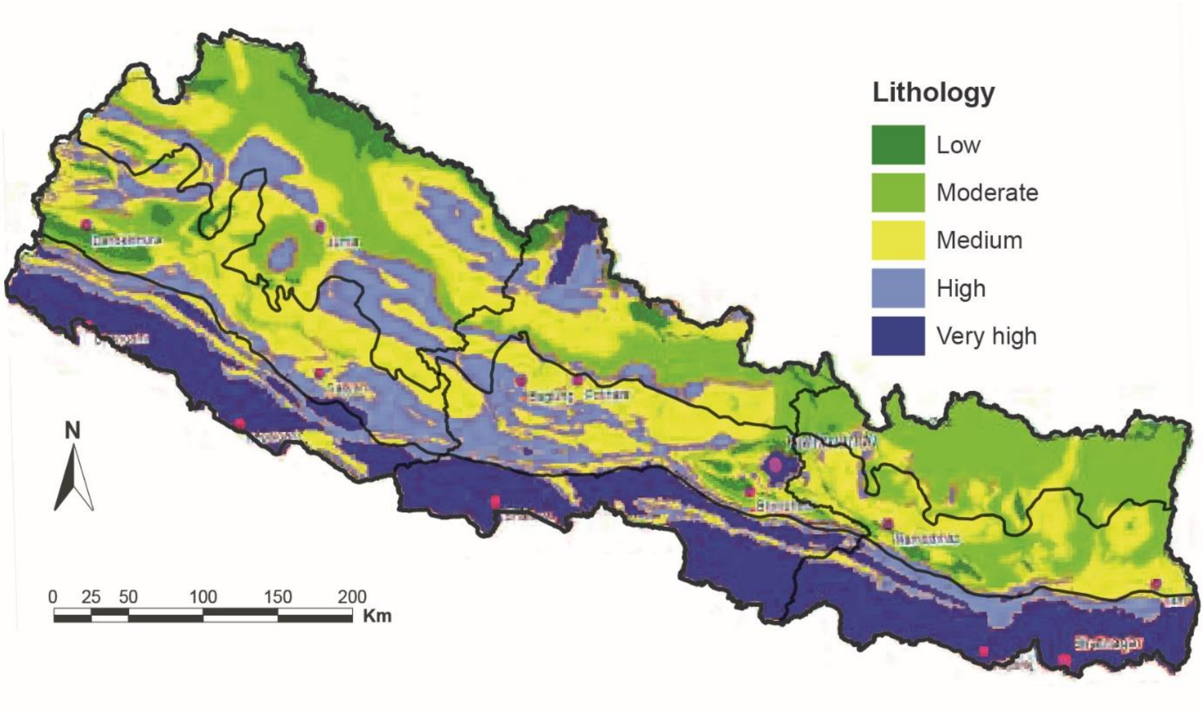


*Figure 3.8. Map of Nepal showing the areas where susceptibility to multi-hazards is low, moderate, medium, high, and very high. The categories and related geological units are listed in Table 4.2.*

*Table 3.2. Geological units of Nepal with susceptibility class describing the units as low, moderate, medium, high, and very high susceptibility.*

| Geological unit | Susceptibiltiy class |
|---|---|
| Quartzites | Low |
| Augen gneisses, banded gneisses | Low |
| Granites | Low |
| Tow mica leucocratic granites with tourmaline | Low |
| Grey siliceous dolomites | Moderate |
| Augen gneisses, granitic gneisses, and feldsphatic schists | Moderate |
| Crystalline limestones | Moderate |
| Grey to greenish grey quartzites, calcareous quartzites | Moderate |
| Gneisses and thin bands of marbles | Moderate |
| Quartzitic schists | Moderate |
| Dolomite underlain by crinoidal limestones | Moderate |
| Muscovite biotite quartz schists | Moderate |
| Crystalline marbles | Moderate |
| Quartz mica schist | Medium |
| Schists metamorphosed rocks | Medium |
| Dark slates with white quartzites | Medium |
| Calcareous silicate rocks and marble bands | Medium |
| Dark gray slates | Medium |
| Crystalline marble | Medium |
| Phyllites quartzites and phyllitic schists | Medium |
| Sandstones | Medium |
| Limestone, sandstone and shale | Medium |
| Phyllites grilstones with conglomerates and white massive quartzites. | Medium |
| Biotite and quartzitic mica schists | Medium |
| Schists quartzites gneisses and calcareous silicate rocks | Medium |
| Muscovite biotite quartz schists quartzites | Medium |
| Schists | Medium |
| Crystalline limestones | Medium |
| Sandstones, chloritic phyllites, lamprophyre sills | Medium |
| Sandstones | Medium |
| Carbonates and dolomitic limestones | High |
| Carbonaceous slates and green shales | High |
| Sandstones | High |
| Continental plateform sediments | High |
| Quartzites with ripple marks interbedded with shales beds | High |
| Calcareous rocks | High |
| Grey shales with intercalation of limestones and quartzites | High |
| Slates with thin limestones | High |
| Sandstones | High |
| Shales with lenses of fine grained fossiliferous | High |
| Calcareous quartzites and quartzitic limestones | High |
| Coarse boulders, conglomerates | High |
| Mainly fluvial and fluvio terrential sediments with local lacustrine clays and marlstones | Very High |
| Alluvium, boulders, gravels, sands and clays | Very High |

### 3.5.4. Statistics

The results of the ANOSIM showed that the slope, river gradient and river density varied significantly by mountainous region (R = 0.71, p-value = 0.003) but not by catchment (R = -0.23, p-value = 0.898).

PCA was used to investigate the variation by zone (Fig. 3.6). This showed that floods are strongly linked to river density which is high in the Lowland zones (Zones 3, 6, and 9). Landslides are more strongly linked to river gradient and slope which are the determining factors on the likelihood of these hazards in Zones 2, 4, 7, and 8. Zone 5 is an outlier in which landslides and floods are both high.

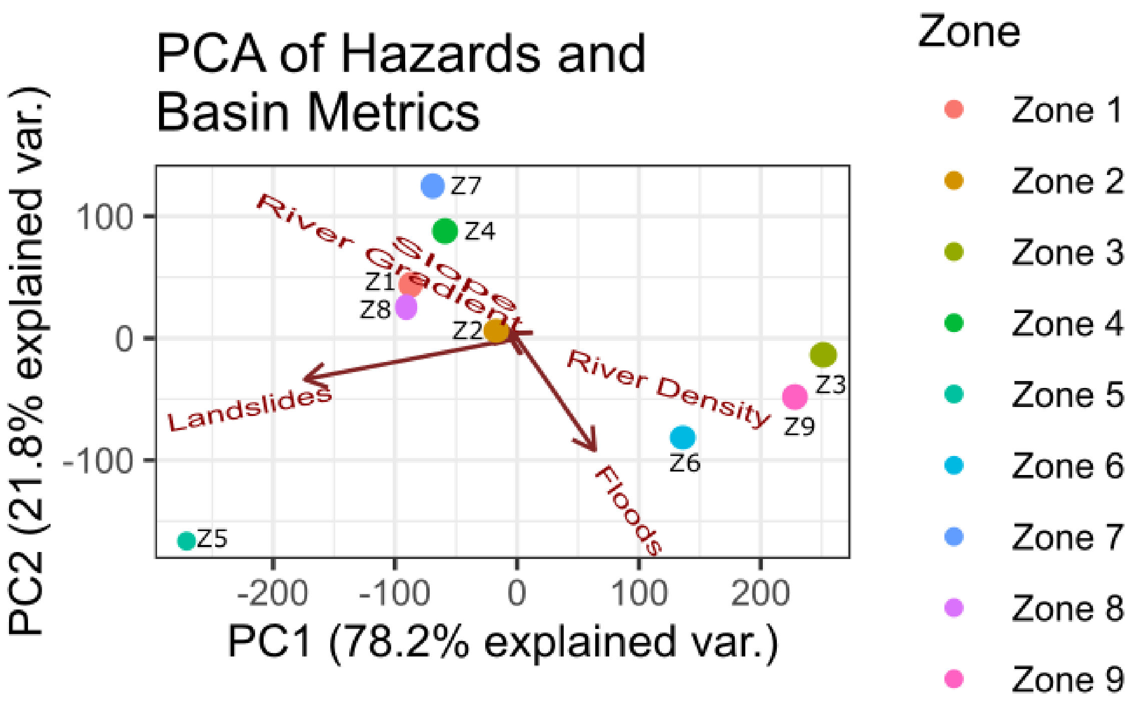


*Figure 3.9. Principal Component Analysis.*

The boxplot below (Fig. 3.9) indicates that slope changes between the mountainous zones, while the river density and river gradient seem to be similar in the High Mountains and Middle Mountains and differ more drastically in the Lowlands.

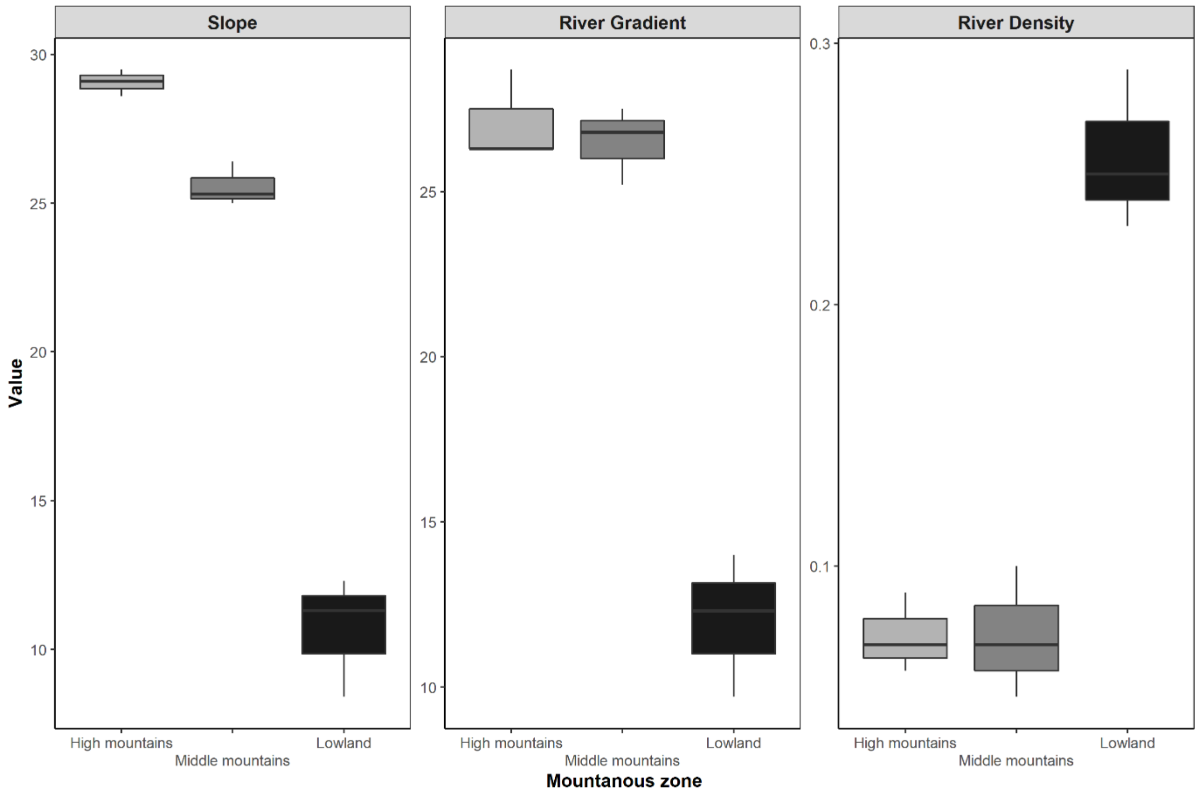


*Figure 3.10. Variation in environmental parameters by mountainous region.*

Another boxplot (Fig. 3.10) shows how hazards vary between the mountainous zones. Floods increase consistently downstream from the High Mountains to the Lowlands, while the landslides are higher in the High Mountains and Middle Mountains and drop off in the Lowlands.

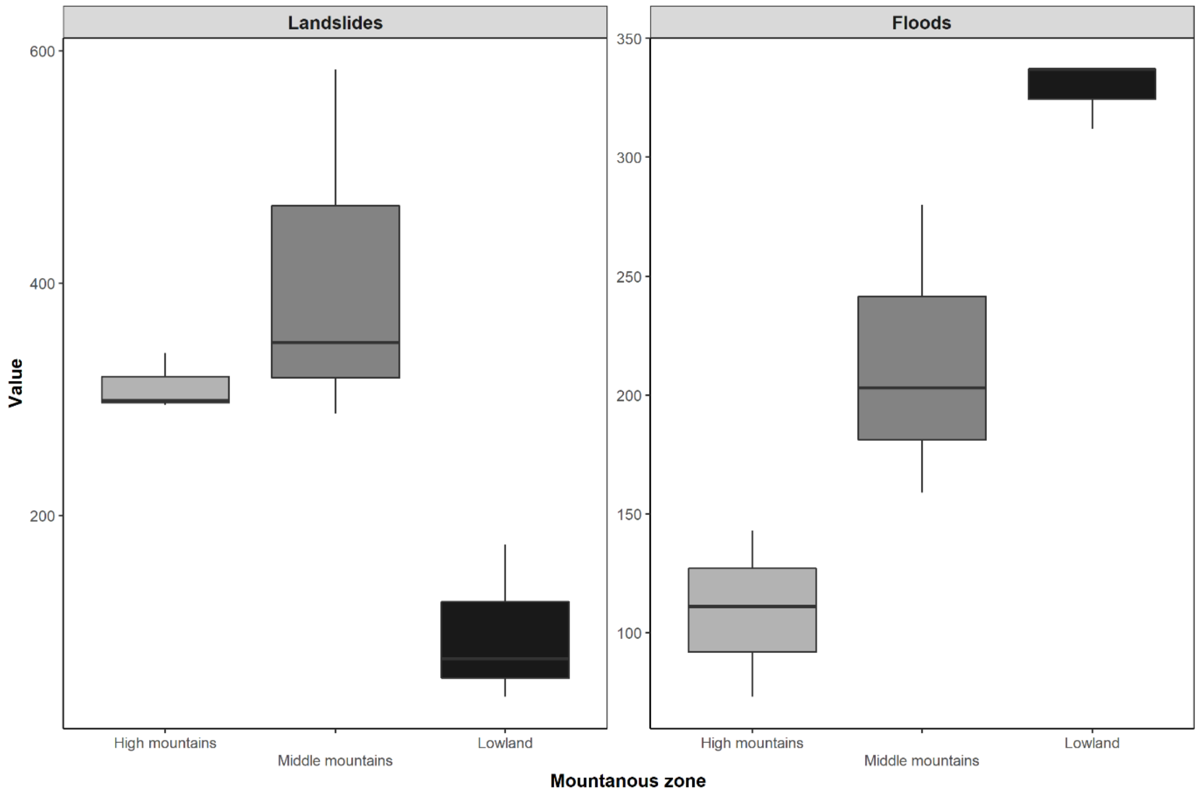


*Figure 3.11. Variation in number of landslides and flooding by mountainous region.*

Based on the two boxplots, landslides are linked to the river gradient and river density, while floods follow a more consistent downstream pattern potentially due to slope.

To conclude this section, we have analysed the patterns of co-occurrence of water-related multi-hazards, described the variations in the summer monsoon, and investigated the potential role of the topography and geographical variation in modifying the hazard occurrence and co-occurrence. This improves our understanding of water-related multi-hazards and has the potential to be used in modelling and prediction of those hazards.

## 3.6. Discussion

This paper has used the ‘Hazards and Environment’ pillar from Chapter 2 to synthesise data on hazard occurrence, rainfall, and landscape characteristics. Our analysis identifies four major findings which we consider are a priority for multi-hazard research on precipitation and landslide/flood incidence in Nepal. These are below. We consider these findings in more detail here by discussing them in relation to extant literatures on each topic.

1. There is space-time variation in the occurrence of water-related multi-hazards in Nepal - with clear evidence of high co-occurrence across the Middle Mountains and lower Gandaki river basin.
2. Water-related multi-hazards appear to be driven by the magnitude and timing of precipitation across Nepal.
3. Water-related multi-hazard co-occurrence was found to be modified by the catchment properties (slope, river density, river gradient, and land cover) by directly influencing the rate of runoff and the catchment storage and release processes.
4. Precipitation patterns were also influenced by catchment properties given the very extreme topography of Nepal creating an orographic effect and funnelling the rainfall up the different valleys depending on their orientation.

Rainfall data gathered from remote sensing shows the progression of the summer monsoon from east to west which may be a key driver of landslides and flooding (Fig. 3.3). The precipitation is likely to act as the power required to initiate the landscape’s mechanism for resultant hazards. The precipitation is high in July in the Koshi basin and decreases in August, whereas in the Gandaki and Karnali basins the precipitation peaks in August (Fig. 3.3). The hazards follow a similar trend indicating that the progression of the monsoon precipitation may be driving the multi-hazards. There is a higher occurrence of flooding in the eastern Lowlands which is explained by the early arrival of the monsoon bringing high precipitation to the lowlands and upstream zones as seen in Figure 3.3. There are less hazards in the Karnali as it is further away from the monsoon progression.

There are numerous studies on the spatial distribution of rainfall in Nepal at a broad scale (Kansakar et al., 2004; Karki et al., 2017); however, these have not yet been related to multi-hazard occurrence and co-occurrence. Kansakar et al. (2004) found that the monsoon duration decreases from east to west with later onset and early withdrawal in the west and that rainfall decreases south to north due to the topography. In the present study, we noted a decrease in rainfall from south to north and that there was a later monsoon onset in the west. However, we did not have sufficient evidence that the duration of the monsoon varied greatly from east to west. The study of Kansakar et al. (2004) investigated the precipitation over 12 months whereas our analysis only looked at the monsoon period which is the timing of the majority of multi-hazards. Looking at the entire year allowed the onset and cessation of the monsoon to be more clearly analysed giving a more reliable indication of the monsoon duration.

Another difference is that Kansakar et al. (2004) used automated weather station data from 222 stations whereas our study used a satellite derived product at 30m x 30m resolution. Krakauer et al. (2013) evaluated remote sensed precipitation products against ground-based weather station observations on a monthly timescale in Nepal. They found that remote sensed data exhibits reasonable skill in giving precipitation data over Nepal, however they do not fully capture the dependence of precipitation on elevation seen by weather stations. However, ERA5 climate reanalysis data is known to have a good consistency of measuring precipitation in mountain environments (Scherrer, 2020). Future work could involve combining satellite data and ground-based measurements to create a more powerful tool for assessing precipitation trends.

Rainfall and hazard occurrence were found to be modified by the landscape characteristics: slope, river density, river gradient, and land cover. The Nepal Hazard Assessment report (2010) describes the landscape of Nepal in detail among many socio-economic factors (ADPC et al., 2010), these have not been related to the hazards unlike in our study. Topography can be seen to modify the progression of the summer monsoon with impacts on the multi-hazard response. Monsoon precipitation is highest in the Lowlands and lowest in the High Mountains. This may be explained by the extreme topography in Nepal as the Lowlands are more exposed to rainfall as it is on the windward side of the mountain range (ADPC et al., 2010). This creates an orographic barrier to rainfall and is the main control on the monsoon progression and therefore the hazards. There is also a funnelling of rainfall up the river valleys in the Middle Mountains which impacts the occurrence of multi-hazards.

There is a higher occurrence of flooding in the Lowlands where rainfall is highest, slope angle is lowest, and river density highest (Fig. 3.4). One of the reasons for this is that the combination of these factors influences local runoff generation (Reaney, 2022). Slope is an important variable for flooding because extensive flat land with very gentle slopes has prolonged inundation, whereas higher slopes provide rapid runoff to remove flood water more quickly and therefore do not become saturated (Ghosh and Kar, 2018; Lane et al., 2004). High river density is important in relation to riverine flooding as high levels of connectivity also cause rapid runoff and increase the likelihood of flooding (Pearson et al., 2022).

On moving north, there was an inversion in the number of hazards with landslides much higher than the number of floods. The High Mountains have a very low number of floods and moderately high numbers of landslides. This could be because there are steep slopes and steep river gradients but low river density, and reduced catchment sizes. Land cover is mostly snow, glacier, and bare rock (Fig. 3.7) . Therefore, flooding is more likely to occur downstream because of snow and glacier melt contributions in addition to the precipitation during the monsoon (Roberts et al., 2021). This trend was seen in our results as lower numbers of floods occurred in the High Mountains than the Middle Mountains. Landslides are highest in the Middle Mountains although differ in number from east to west. The highest number of landslides is in the Middle Mountains of the Gandaki in July. Flooding is also relatively high across the Middle Mountains particularly in the Gandaki basin which could be caused by the snowmelt. Kirschbaum et al. (2020) also found that the rate of increase in landslide activity is expected to be greatest over areas covered by current glaciers and glacial lakes, potentially exacerbating the impacts of cascading hazards on populations downstream. Likewise, Ruiz-Villanueva et al. (2017) found devastating impacts of floods downstream of glaciated areas, these were related to snow melt and intense precipitation. Broadly the Middle Mountains have steeper slopes and higher river gradients indicating that there are steep valley sides where landslides occur. Steep valley sides may provide a barrier to rainfall locally, while the high peaks may create weather extremes, such as cloudburst phenomena which are localised intense downpours (Ruiz-Villanueva et al., 2017).

Land cover has changed significantly over the last 20 years due to both anthropogenic activity and natural factors and impacted hazard risk in multiple ways (Paudel et al., 2016). Studies based on historical evidence and satellite imagery have shown an increase in cropland areas in Nepal and a decrease in forest and snow/glacier coverage. According to the agricultural census of Nepal (GoN, 2023), there has been a 7.8% increase in the number of families engaged in farming over the last 10 years. Transformation from forest to agricultural crops or grassland for grazing can increase landslide predisposition by decreasing the strength provided by tree roots and increasing the erosive forces by rain drops (Chaudhary et al., 2016; Muñoz-Torrero Manchado et al., 2022). The removal of forest for agriculture also results in compaction of soil with a consequent decrease in infiltration capacity and an increase to surface run off, hence causing flooding (Gilmour et al., 1987). There has also been an expansion in urban areas as a result of population increase and a decrease in grassland due to climatic effects. (Paudel et al., 2016). These changes have made the landscape more susceptible to landslides and flooding (Vuillez et al., 2018).

The spatial variation in geology is also a control on the occurrence of multi-hazards as different geological units have different susceptibilities to active geomorphological processes (Dahal et al., 2008). This parameter is difficult to assess as only a general geological description is available. Rock strength and fracturing are the most important factors to evaluate lithological characteristics, and these characteristics can vary greatly over short distances (ADPC et al., 2010).

Plutonic rocks, such as granite, will usually be strong and represent low risk of multi-hazard occurrence. Strength of metamorphic rocks is variable, but these rocks often have planar structures such as foliation and therefore may represent higher risk than plutonic rocks. Lava rocks will usually be strong, but may be associated with weak material, like Tuff. Sedimentary rocks, like sandstones and shales, are often very weak.

Our results conclude that the Lowlands of Nepal are generally composed of fluvial sediments which are highly susceptible to multi-hazards, the middle mountains have slightly less susceptibility with sandstone and other sedimentary rock, whereas the high mountains have mixed geology and mixed susceptibility. The pattern of co-occurrence of multi-hazards does not follow this trend precisely as the highest co-occurrence of multi-hazards are in the Middle Mountains. This indicates that other controls are likely to be important in the occurrence of multi-hazards.

Within the South Asian Monsoon, the rainfall signatures, in terms of precipitation magnitude, duration, frequency, and antecedent conditions, must be analysed to investigate the way in which the local weather conditions drive landslides and floods. A number of studies concluded that extreme precipitation drives landslides whilst others found that it is as a result of antecedence (Dahal and Hasegawa, 2008; Dai and Lee, 2001). This will be the focus of Chapter 4 in relation to both hazards, rather than landslides alone.

Muñoz-Torrero Manchado et al. (2021) found a strong correlation between the annual number of landslides and the accumulated precipitation in a study located in far western Nepal. They also found that anthropogenic drivers play a main role in driving landslides, namely road-cutting and deforestation. From our findings there are multiple factors that modify the rainfall and hazard occurrence thus road building must also be investigated as a potential causative factor of landslides and flooding. In addition, changes in land cover through time have not been analysed in this study and may be a source of future research.

Overall, the framework from Chapter 2 has proved invaluable in structuring our study. It has informed the ways in which data was collected in the paper, and how it was analysed. The framework also provided direction based on a bibliometric analysis and investigation of the existing approaches. Taken together it has therefore provided a clear research design for undertaking research on water-related multi-hazards.

## 3.7. Conclusion

This chapter has provided a preliminary analysis of the interconnections between hydrological and geomorphological drivers of multi-hazards across Nepal. In doing so we have deployed the physical geographic element of the framework outlined in Chapter 2 to investigate the natural controls and drivers of hydrologically induced landslides and floods in the country. These data have been aggregated at a regional scale and through analysis of multi-hazards, rainfall, and basin properties have yielded many new insights into multi-hazard processes at the national scale.

This analysis furthers our knowledge of the occurrence and co-occurrence of landslides and floods and how they interact with the South Asian Monsoon and the diverse landscape of Nepal. In particular we have shown that the spatial patterns of water-related multi-hazards vary according to both hydrological and physiographic factors. The results show that there is space-time variation in the patterns of occurrence of water-related multi-hazards in Nepal and evidence of high co-occurrence across the Middle Mountains and lower Gandaki river basin, this may be caused by variation in the magnitude and timing of precipitation either by direct input to the catchment or by antecedence. In addition, the basin properties (slope, river density, river gradient, and land cover) appear to also have an influence on the rainfall patterns and the multi-hazard co-occurrence. These landscape characteristics effect broadscale rainfall patterns through the steep slopes of the Middle and High Mountains, creating an orographic barrier to precipitation and the high river gradients causing localised weather anomalies like intense downpours. The multi-hazard co-occurrence is also modified by the basin characteristics which control the catchment storage and release processes.

This examination has identified national scale patterns of water-related multi-hazards in Nepal that require further evaluation in the form of testing the characteristics of rainfall (magnitude, frequency, duration, and antecedence) and some of the anthropogenic factors (e.g., road building) that affect the landscape, which will be the focus of Chapter 4. The framework from Chapter 2 also considers another disciplinary perspective in understanding the socio-economic parameters surrounding water-related multi-hazards. This is described in the second pillar of the framework which has not been addressed here but will be the focus of Chapter 5.

# Chapter 4 – Understanding space-time interactions between hydrometeorology and catchment controls on water-related multi-hazards

## 4.1. Abstract

Precipitation is a complex driver of water-related multi-hazards. Building on the analysis from Chapter 3 and the framework developed in Chapter 2, I investigated the space-time patterns of multi-hazard co-occurrence in relation to rainfall metrics, catchment properties, anthropogenic factors, and large-scale climate controls of local weather conditions in Nepal. In Chapter 3, it was proved that the timing and magnitude of rainfall throughout the South Asian Monsoon was driving water-related multi-hazards and that the catchment properties (slope, river density, river gradient, land cover, and geology) appeared to be modifying both the rainfall and hazard occurrence. In this chapter, rainfall and river basin properties were investigated in greater detail, using the same study area and similar data to Chapter 3. Heatmaps of hazard occurrence and rainfall metrics (magnitude, frequency, duration, and antecedence) and time series of daily rainfall for 10 years out of my 20-year data set were created. The Southern Oscillation Index over the 20-year time period and the road density in each zone was looked at to investigate other catchment controls on water-related multi-hazards. These analyses enabled the inference of the process interactions and concluded that a combination of hydrometeorological and catchment properties

control water-related multi-hazards. This knowledge must be related to the social vulnerability of people and places to fully understand water-related multi-hazards in a place-based approach, this will be the focus of Chapter 5.

## 4.2. Introduction

Landslides and floods, water-related multi-hazards, are triggered by hydrometeorological conditions as an immediate cause or as a result of antecedence (Nayava et al., 2022). However, catchment conditions moderate these hydrometeorological drivers to create different space-time patterns in water-related multi-hazards (Chalise et al., 2019).

Rainfall processes and the associated landslides and flooding are highly complex and are affected by many factors (Ran et al., 2012). In terms of rainfall, it is not only the amount that falls that triggers these multi-hazards but it may be the distribution of precipitation over time (Breinl et al., 2015). The most commonly investigated rainfall metrics include rainfall magnitude, cumulative rainfall, rainfall timing, rainfall frequency, rainfall intensity, rainfall duration, and antecedent rainfall (Dahal and Hasegawa, 2008). In mountainous regions, there can be prolonged rainfall of several days to weeks or short high magnitude cloudbursts where the rainfall over a particular area exceeds 100 mm in an hour (Kirschbaum et al., 2020). This has implications on the occurrence and co-occurrence of water-related multi-hazards.

In terms of antecedence, water infiltration in hillslopes causes landslides by changing pore water pressure, reducing shear stress, and resulting in slope instability (Iverson, 2000). Patterns of evapotranspiration, soil saturation, infiltration, and runoff generation are antecedent factors that play a role in landslides and riverine flood generation (Nied et al., 2014). These conditions may be hypothesised by some researchers to be less important in the occurrence of flash floods which are usually caused by heavy or excessive rainfall in a short period of time (e.g. Bischiniotis et al., 2018).

There is a strong linkage between large-scale atmospheric circulation patterns and the rainfall accumulation and distribution (National Centres for Environmental Information, 2022). Large-scale atmospheric circulation patterns, namely the El Niño-Southern Oscillation (ENSO), effect the South Asian Monsoon which in turn may have an impact on multi-hazard occurrence and co-occurrence (Bohlinger and Sorteberg, 2018; Petley et al., 2007; Shrestha, 2000). There are other natural factors including topography, slope, river density, river gradient, land cover, and geology which were investigated in Chapter 3 and found to effect both the rainfall and the multi-hazard occurrence and co-occurrence in Nepal.

Anthropogenic factors include land use change, road building, construction, and mining (Froude and Petley, 2018). Road building and land use change are particularly key to causing slope instability and drainage congestion (Adhakari, 2013; Muñoz-Torrero Manchado et al., 2021; Petley et al., 2007). Informal road building causes landslides in a number of different ways, for example excavated material on the downslope side of the road, poor road drainage, over steepened road cuts, and the removal of vegetation (McAdoo et al., 2018). Roads and bridges are often destroyed by these hazards too, for example, part of the east-west highway that connects all Terai districts was washed out by flood waters in September 2007 (Adhakari, 2013). Figure 4.1 shows the cascade of processes controlling water-related multi-hazards including hydrometeorological drivers, large-scale climate variability, landscape characteristics, and anthropogenic factors.

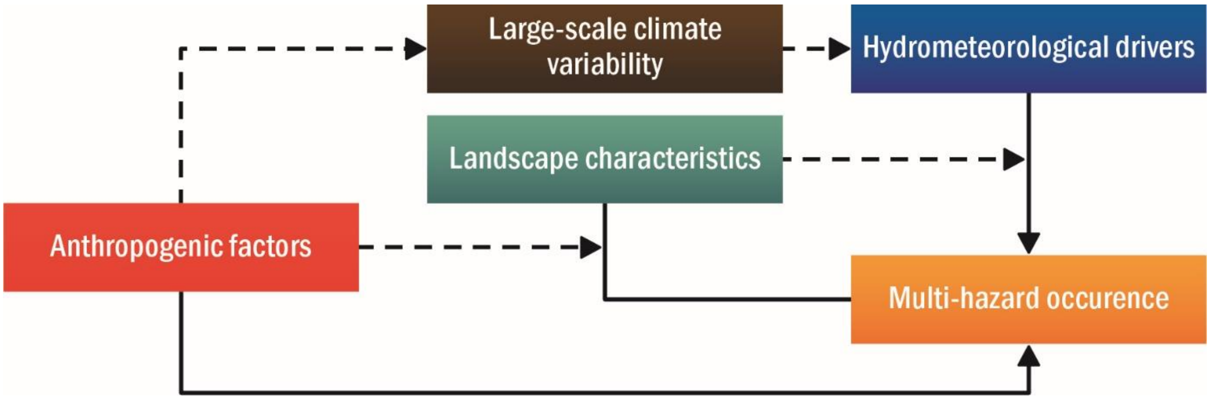


*Figure 4.1. Cascade of processes controlling water-related multi-hazards including hydrometeorological drivers, large-scale climate variability, landscape characteristics, and anthropogenic factors. The solid arrows indicate direct interconnections between the controls and multi-hazard occurrence. The dashed arrows show how these controls affect multi-hazards by influencing the other controls.*

In Nepal, water-related multi-hazards cause over a hundred fatalities each year. Over 87% of these are known to be induced by rainfall according to a calculation based on the DesInventar report 2015 (UNDRR, 2022). In addition, they disrupt agricultural productivity, damage infrastructure, and cause serious economic disruption on multiple scales (Adhakari, 2013; Nayava et al., 2022). Therefore, Nepal is an important case study for understanding the relationship between multi-hazard occurrence, water-related processes, geomorphology, and human interaction.

Nepal is dominated by shallow rock-falls and slides pervasive across the Himalaya as well as both riverine and flash floods (Roberts et al., 2021). These hazards are highest during the monsoon season, June to September indicating that rainfall and antecedent conditions have an important effect (Petley et al., 2007). There must be an understanding of the rainfall conditions required in the lead up to landslides and flooding. This involves looking in more detail at the rainfall metrics (rainfall magnitude, rainfall frequency, rainfall duration, and antecedent rainfall).

In addition, road construction has acted as a new trigger for landslides in Nepal (Nayava et al., 2022; Petley et al., 2007). The Nepal road network is rapidly expanding and has gone from having 4,740 km of drivable roads in 1998 to 12,494 km in 2014 (Vuillez et al., 2018). Thus, it is important to consider road density, as well as rainfall when understanding multi-hazards in Nepal.

In Chapter 2, we developed a framework for understanding water-related multi-hazards. Elements of this framework have been applied in this work. A broad scale analysis of the spatial variation of multi-hazards in Nepal has been carried out in Chapter 3. The findings of this chapter were that the occurrence of hydrologically induced multi-hazards varies in both space and time, as does the rainfall during the monsoon. These variations showed that catchment properties and rainfall characteristics are likely to modify the hazard occurrence and co-occurrence. These rainfall and landscape factors will be investigated in more detail in this chapter by using heatmaps and time series analysis. This chapter builds on Chapter 3 by using a nested approach to further assess the space-time interactions between hydrometeorology and catchment controls on water-related multi-hazards and to understand the active processes occurring in Nepal.

## 4.3. Methodology

In this chapter, the same study area has been used and the data has been derived in a similar way as in Chapter 2, as such this will not be repeated in full here. A refined methodology was used based on more in-depth analysis of rainfall and basin properties. The following sections describe the analytical framework for this study and the data analysis conducted.

### 4.3.1. Study area and analytical framework

In Chapter 2, Nepal was delineated according to nine natural zones defined by drainage basin and physiography. The same nine zones will also be used for analysis in this chapter (Fig. 4.2).

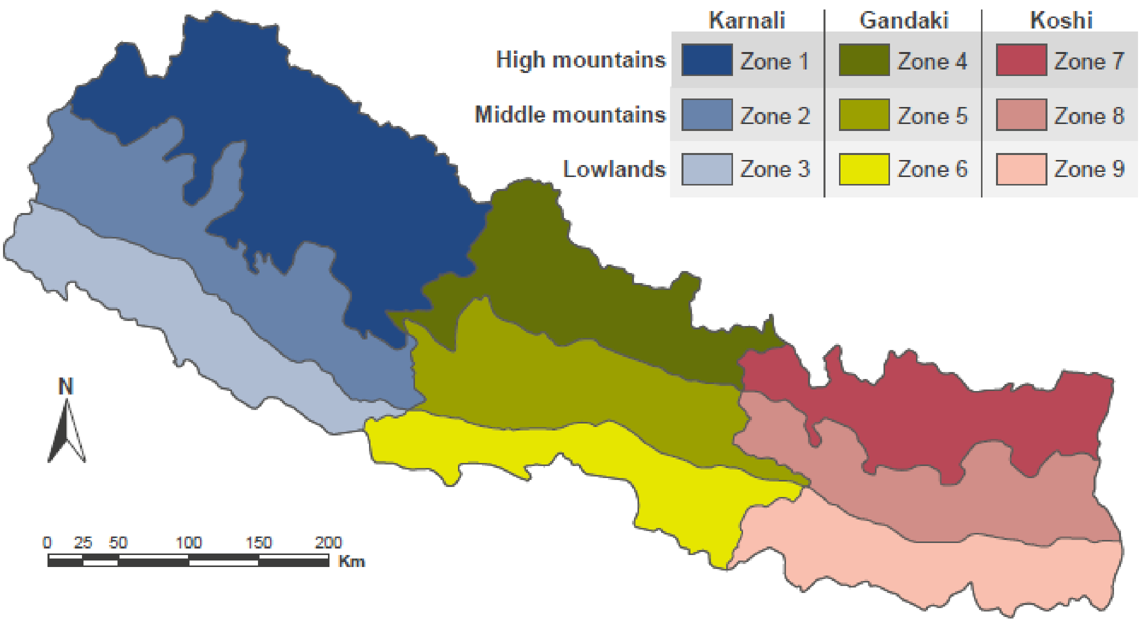


*Figure 4.2. Nepal delineated by nine natural zones defined by drainage basin and physiography.*

### 4.3.2. Data sets

The landslide and flood data were compiled from the Disaster Inventory System (DesInventar) and the daily rainfall was derived from the ERA5 satellite precipitation dataset, as in Chapter 2.

The Southern Oscillation Index (SOI), downloaded from the National Centres for Environmental Information (NCEI), was also explored as a potential large-scale atmospheric driver. This was chosen as Hannah et al. (2005) showed some links between precipitation, runoff, and the SOI. The SOI is a standardised index based on the sea level pressure difference across the Pacific Ocean (National Centres for Environmental Information, 2022). It measures the large-scale variations in air pressure during El Niño and La Niña episodes which has an impact on the South Asian Monsoon. Negative SOI values correspond to uncharacteristically high ocean water temperatures across the eastern tropical Pacific which is known as an El Niño episode. La Niña is when there are positive SOI values which correspond to cold waters. El Niño episodes are associated with less strong monsoon rainfall in Nepal and the opposite with La Niña (Shrestha, 2000).

Recent road network data was obtained from open street map (Geofabrik, 2023). These were in the form of GIS layers which were vectors of primary, secondary, and tertiary roads, tracks, and motorways.

### 4.3.3. Data analysis

Assessment of the South Asian Monsoon as a driver of multi-hazard activity involved looking specifically at the monsoon months, June, July, August, and September. The rainfall and water-related multi-hazards during these months were investigated over a

20-year time period for each of the nine defined zones. This time period was chosen as the disaster inventory only records until 2013 in Nepal and data previous to 1993 was excluded due to recording bias and uncertainties.

In this analysis, I have compared landslide and flood occurrence to four different monthly rainfall metrics (rainfall magnitude, rainfall frequency, rainfall duration, and antecedent rainfall) (Table 1). This builds on Chapter 3 which looked at the mean, maximum, and minimum rainfall over the 20-year time period for each of the nine zones for the monsoon months. It was found that this had an effect on the spatial distribution and timing of multi-hazard occurrence and co-occurrence.

*Table 4.1. Definition of rainfall metrics.*

| **Precipitation Metrics** | **Definition** |
|---|---|
| Magnitude (mm) | The maximum rainfall occurring on a single day throughout the month. |
| Frequency (days) | The number of days in which the rainfall is above the $75^{th}$ percentile throughout the month. |
| Duration (days) | The number of consecutive days in which the rainfall is above the $75^{th}$ percentile per month. |
| Antecedent Rainfall (mm) | The mean rainfall occurring over every five day period of the month. |

To explore the spatial and seasonal patterns of the hazards and rainfall metrics, I created heatmaps using the ggplot geom_tile function in R (R Core Team, 2022) of landslide occurrence, flood occurrence, rainfall magnitude, rainfall frequency, rainfall duration, and antecedent rainfall in every month of the monsoon in every year of the chosen time period for each of the nine zones. Heatmaps are a useful data visualisation tool because the colour coding can be used to highlight times and places in which there are high or low concentrations of the given variable (van Loon and Laaha, 2015). This allowed analysis of the interconnections between hazard occurrence and rainfall by comparing these variables and how they overlap.

By interpretation of the heatmaps, hazard occurrence was used to frame the research by identifying five years in which the occurrence of both hazards was high and five years when the occurrence of both hazard events was low. These years were then looked at more closely through time series analysis as line graphs using the ggplot line_plot function in R to see if there were similarities in rainfall across the respective years. These plots showed the daily timing and amount of rainfall throughout those years which could be used to look in more depth to see whether the rainfall characteristics are driving the multi-hazards.

In addition, the SOI was plotted as a bar plot using the ggplot bar_plot function in R as an annual time series for the observed 20-year time period to investigate if there was a relationship between negative/positive SOI values coinciding with high/low multi-hazard occurrence. This was done to understand large-scale atmospheric drivers of local rainfall and the associated multi-hazard occurrence.

I also investigated the effects of road building using ArcGIS analysis version 10.7.1 (ESRI, 2018) to calculate the density of primary, secondary, and tertiary roads, tracks, and motorways within the nine zones using the ‘Spatial Analysis’ toolset. Then, the sum of all road density metrics was calculated for each of the nine zones to give the total density of roads.

The process interactions can be inferred by analysing these space-time patterns of multi-hazards, the hydrometeorology and large-scale climate controls that drive them, and the catchment properties and anthropogenic activity that modify their occurrence.

## 4.4. Results

As outlined in the methodology, this analysis takes a nested approach to multi-hazard analysis. The following sections will include the results of the heatmap analysis, the time series plots, the SOI fluctuations, and the road density calculations in order to compare multi-hazard occurrence with the various drivers and modifiers.

### 4.4.1. Heatmap analysis of hazard and rainfall metrics

In the below section, there is a detailed account of the fluctuations in hazards and rainfall metrics throughout the 20-year time period using heatmaps.

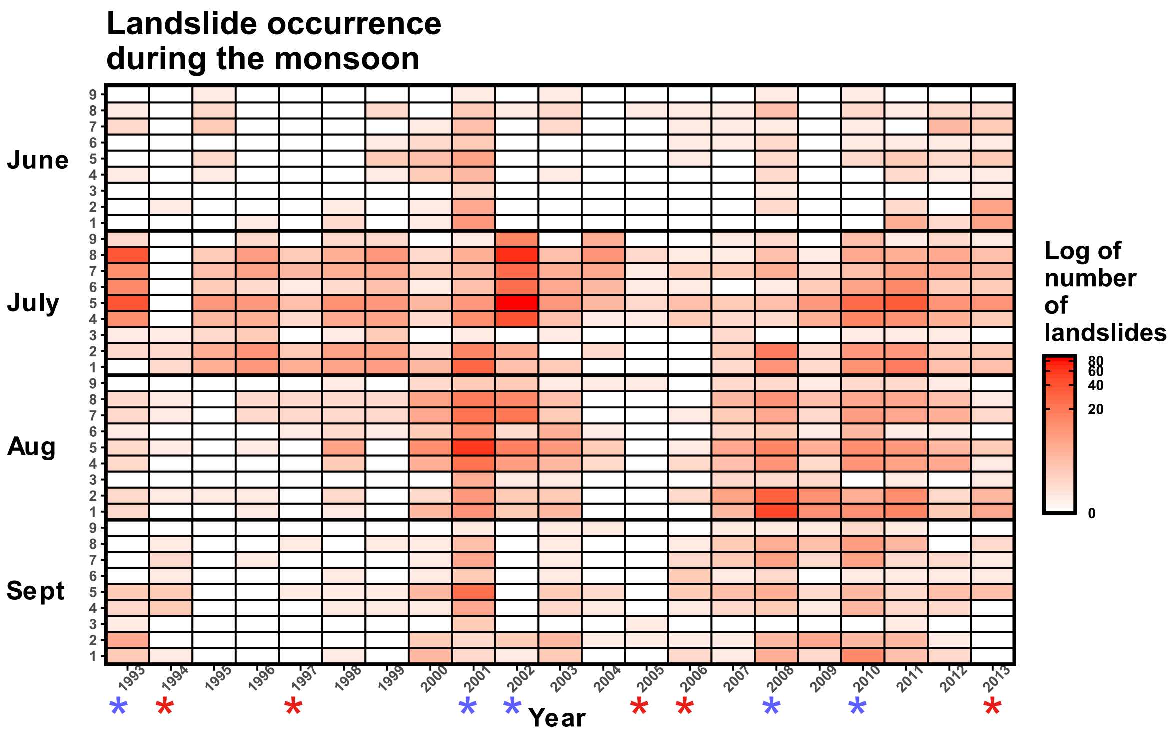


*Figure 4.3. Heatmap of log of number of landslides per year during the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis.*

Landslide occurrence during the monsoon for the nine zones is shown in Figure 4.3. The predominant trend is that there are a greater number of landslides in July. Years in which this trend is not seen are 2000, 2001, and 2008, when landslide occurrence is higher in August. There are low numbers of landslides in June and September at between 0 and 24 landslides in all of the zones throughout the 20-year time period. There are a number of years when numbers of landslides are extremely high; 1993, 2001, 2002, and 2008. In July of 2002, they reach 88 landslides. Landslide occurrence is higher in the Middle Mountains and High Himalaya (Zones 1, 2, 4, 5, 7, and 8) with the maximums ranging in July from 19 in Zone 9 to 88 in Zone 5. However, there are a higher number of landslides in July in the Lowlands of the Central Gandaki basin (Zone 6) reaching 12, than in the other Lowland Zones which only reach 6.

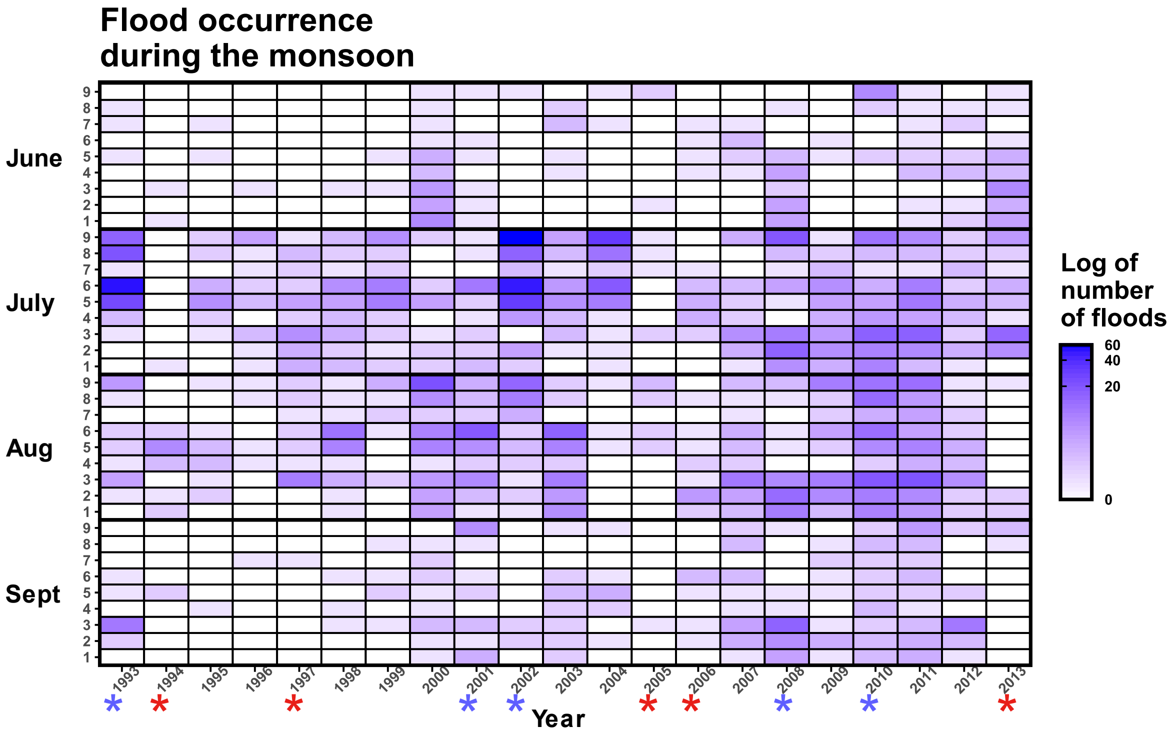


*Figure 4.4. Heatmap of log of number of floods per year during the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis.*

Flood occurrence during the monsoon for the nine zones is shown in Figure 4.4. There is an even spread of years when the highest number of floods occurs in July and years when the highest number is in August with some years when the totals are very similar. Years when flood occurrence is highest in August include 1994, 2000, 2001, 2003, 2005, 2006, and 2013. Flood numbers range between 0 and 21 over July and August in most of the latter years 2009, 2010, 2011, and 2012. There are between 0 and 8 floods in June and between 0 and 16 floods in September with the majority of values 0 throughout the time period, apart from 2000 and 2008 when flooding is moderate throughout the monsoon. Flooding is particularly high in 1993, 2001, 2002, 2004, 2008, and 2010 reaching the highest value of 63 in July 2002. Flood occurrence is highest in the Lowlands (Zones 3, 6, and 9) with a number of floods also occurring in the Middle Mountains (Zones 2, 5, and 8), whereas numbers are low in the High Himalaya (Zones 1, 4, and 7).

On comparing Figures 4.3 and 4.4 there is evidence of high co-occurrence of landslides and flooding in 1993, 2001, 2002, 2008, and 2010. These years will be looked at more closely using time series analysis of precipitation throughout the monsoon. In July 1993 there is high co-occurrence in the Middle Mountains of the Gandaki and the Koshi (Zones 5 and 8) whereas there is a lower occurrence of both hazards in the Karnali (Zones 1, 2, and 3). There is also a low occurrence of both hazards in August 1993. Co-occurrence is high in August in 2001 predominately in the Middle Mountains of the Gandaki (Zone 5). In July 2002 co-occurrence is high in the Middle Mountains of the Gandaki and Koshi (Zones 5 and 8) whereas there is a lower occurrence of both hazards in the Karnali (Zones 1, 2, and 3). There is also high co-occurrence in July and August in 2008 and 2010 in the Middle Mountains of the

Gandaki and Karnali (Zones 5 and 2) while there are less hazards in the Koshi (Zones 7, 8, and 9).

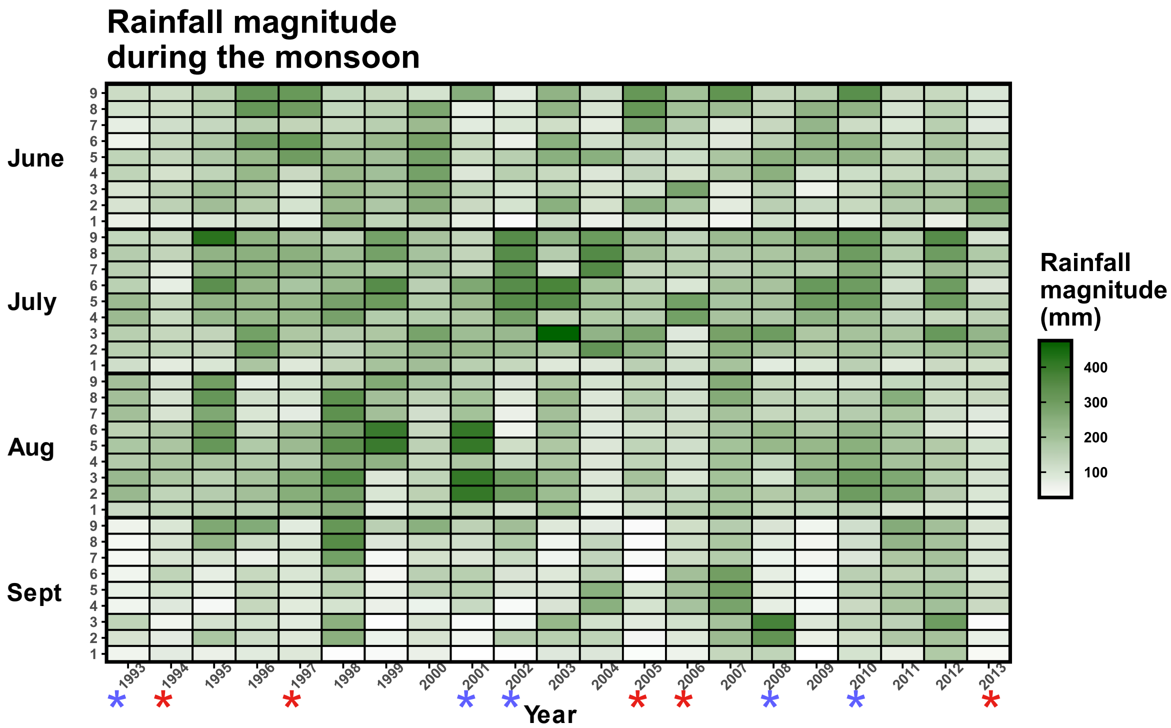


*Figure 4.5. Heatmap of rainfall magnitude per year during the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis.*

Rainfall magnitude varies with most of the high events in July but some in June and August (Fig. 4.5). Years with extremely high rainfall events are 1995, 1998, 1999, 2001, 2003, 2004, and 2008. In these years the maximum monthly rainfall exceeds 350 mm per day in certain zones for some months. There are high magnitude events throughout the zones, however there are a higher number in the Koshi basin (Zones 7, 8, and 9).

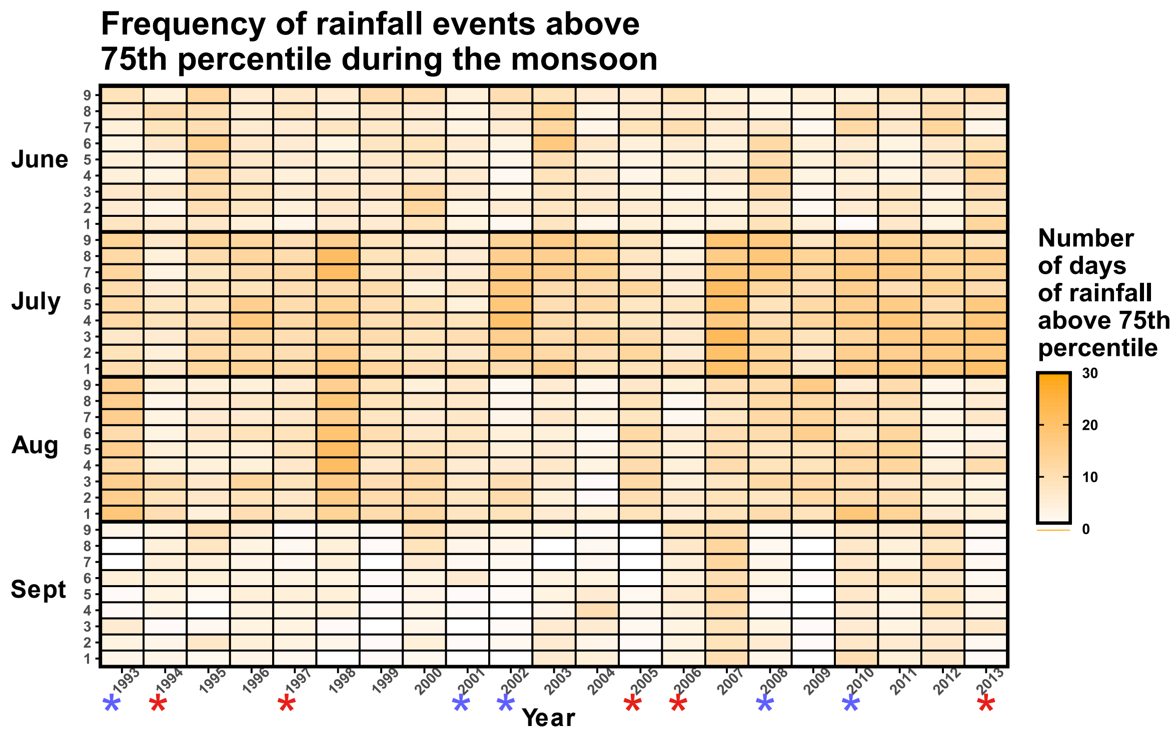


*Figure 4.6. Heatmap of rainfall frequency per year during the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis.*

The frequency of rainfall is measured by number of days above the 75$^{th}$ percentile in that month (Fig. 4.6). High frequency rainfall tends to be in July and August. Years when there are the most days above the 75$^{th}$ percentile are 1998, 2002, 2007, and 2013, when there are 20 or more days. The spatial distribution of high frequency rainfall is quite even over the three drainage basins and physiographic zones meaning that when rainfall frequency is high it is high across all regions and when low vice versa.

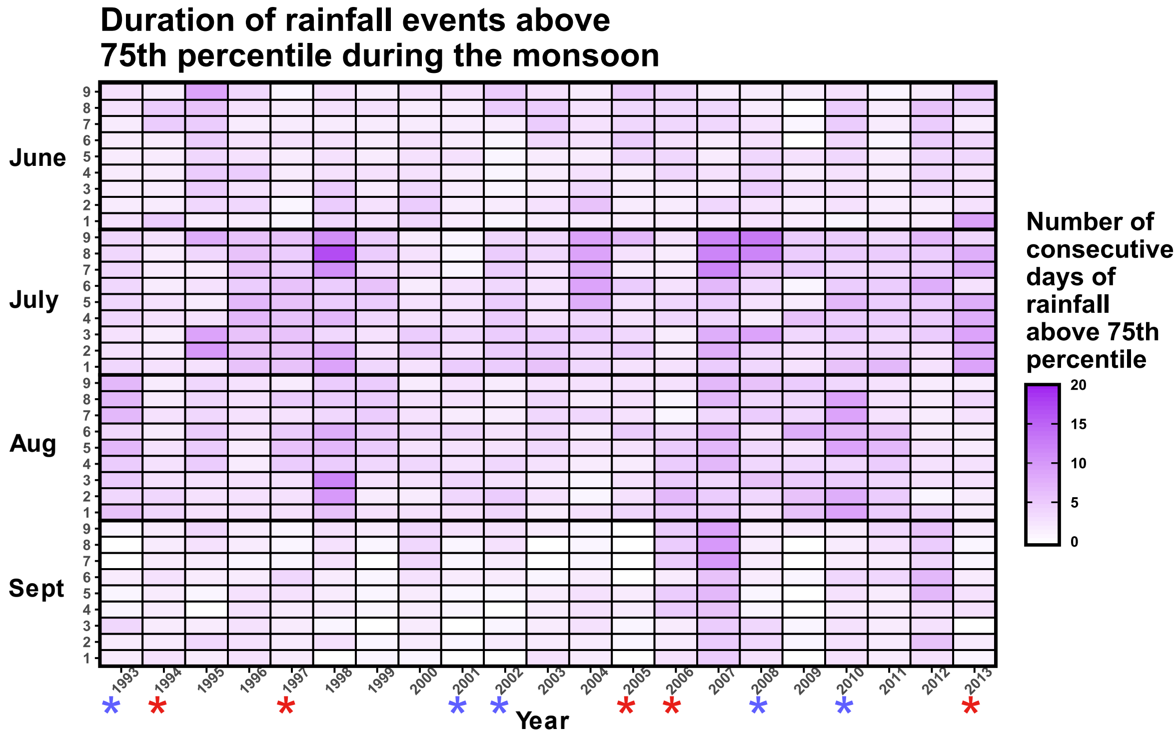


*Figure 4.7. Heatmap of rainfall duration per year during the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis.*

The duration of rainfall is measured by the number of consecutive days above the 75$^{th}$ percentile in that month (Fig. 4.7). Years when there are the most consecutive days above the 75$^{th}$ percentile are 1998, 2007, and 2008. The spatial distribution of high duration rainfall is higher towards the Karnali river basin.

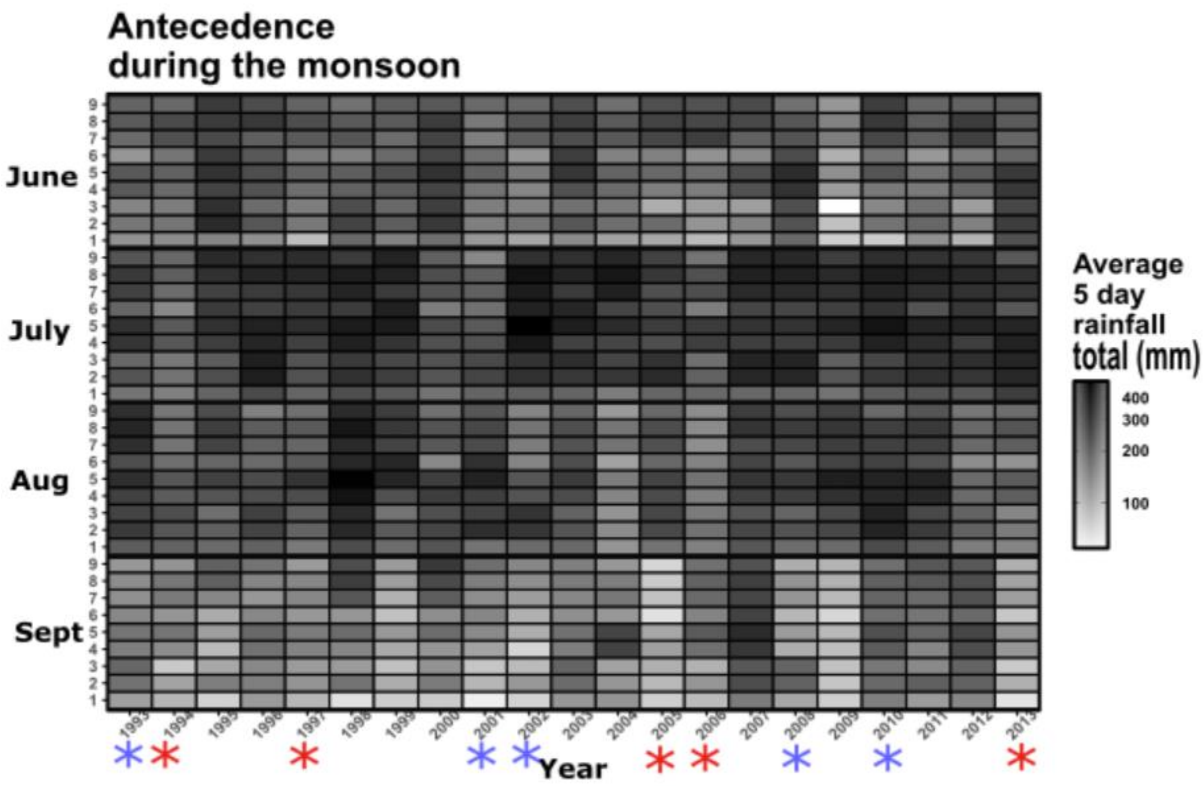


*Figure 4.8. Heatmap of antecedent rainfall suring the monsoon months. Blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated further through time series analysis*

The antecedent rainfall is measured by taking an average of the total rainfall over every five-day period throughout each month (Fig. 4.8). Years when antecedence is particularly high include 1998, 2002, 2007, and 2010. The spatial distribution of antecedent rainfall is greater in the eastern Koshi basin (Zones 7, 8 , and 9).

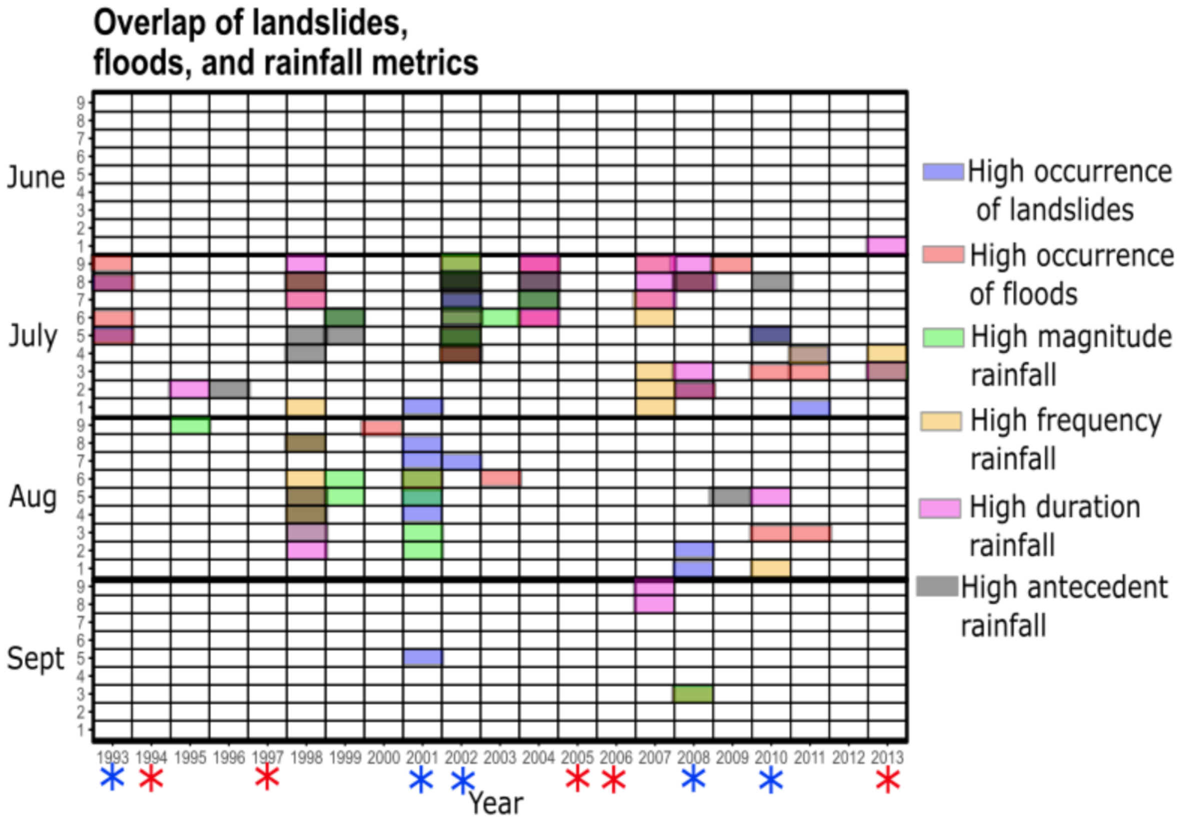


*Figure 4.9. Heatmap showing the overlap of the top 20 hazard occurrences and rainfall parameters during the monsoon months throughout the time period analysed. The blue asterisks indicate years when hazard occurrence is high and red asterisks indicate years when hazard occurrence is low. These years will be investigated through time series analysis.*

The overlap of hazards and rainfall metrics can be seen in Figure 4.8. This shows that there is an overlap of all parameters in July 2002 in Zones 4, 5, 6, 7, 8, and 9. There are a few other overlaps but overall most of the rainfall parameters do not overlap in the same time and place as the hazards.

### 4.4.2. Precipitation time series analysis

Based on the heatmaps, the five years in which both hazards are lowest and the five years when both hazards are highest have been plotted as time series to examine the precipitation trends in more depth. The years in which there both hazards are highest are 1993, 2001, 2002, 2008, and 2010. The years in which both hazards are lowest are 1994, 1997, 2005, 2006, and 2013.

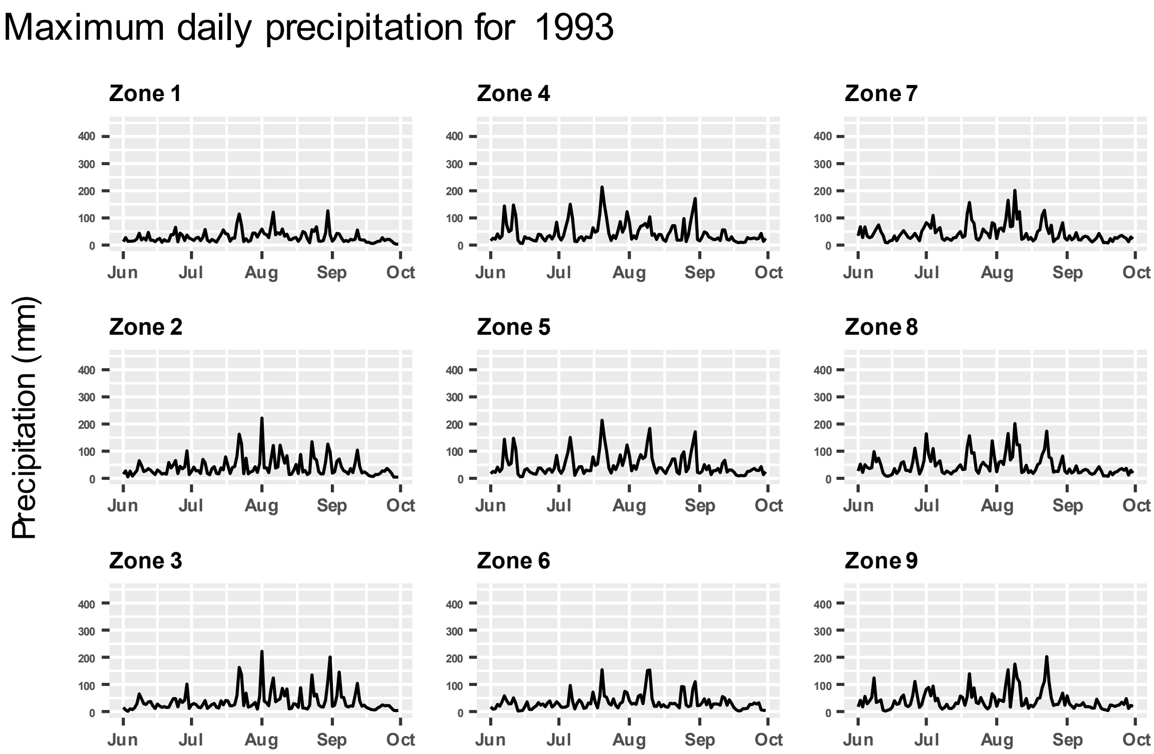


*Figure 4.10. Time series of daily maximum precipitation in 1993, in which year hazards are high.*

In July 1993, there are a high number of hazards in the Gandaki and Koshi basins (Zones 4, 5, 6, 7, 8, and 9) throughout the monsoon. This excludes the Karnali basin (Zones 1, 2 and 3) in which there are only 4 hazards occurring over the whole basin in July and then slightly higher, but still low numbers of hazards in August and September with 10 and 24 respectively (Fig. 4.3 and 4.4). There are only low magnitude rainfall events reaching a maximum of 222 mm in 1993 (Fig. 4.5), however the frequency and duration of high rainfall events above the 75$^{th}$ percentile is moderate to high over all zones with a maximum frequency of 18 days and a maximum duration of 7 days, but this is to a lesser extent over the Karnali (Fig. 4.6 and 4.7). The time series data shows that there is the greatest number of high rainfall events in the Gandaki and Koshi basins (Zones 4, 5, 6, 7, 8, and 9) (Fig. 4.9). Daily rainfall is particularly low in June in the Karnali river basin (Zones 1, 2, and 3) reaching 101 mm whereas it is moderately high in June in the Gandaki and Koshi reaching 147 mm.

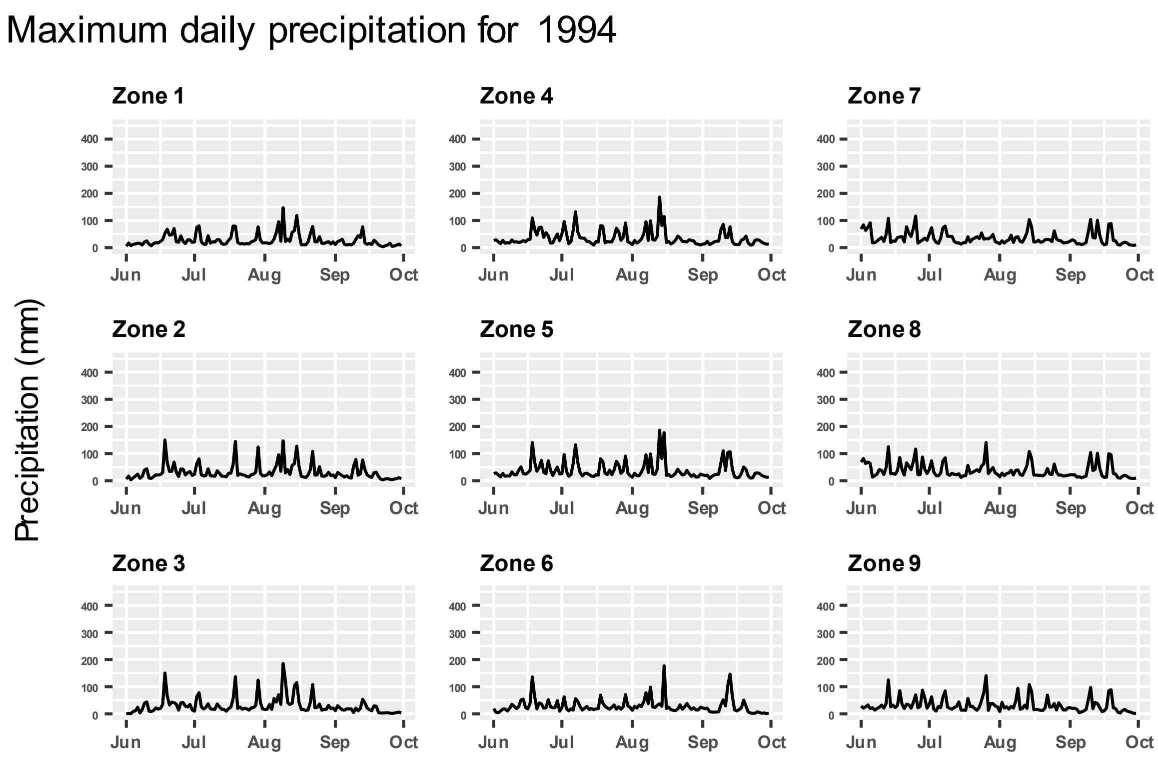


*Figure 4.11. Time series of daily maximum precipitation in 1994, in which year hazards are low.*

The year 1993, where numbers of landslides and flooding are high, is followed by a year in which there are between 0 and 10 hazards occurring within any month in any zone throughout the monsoon (Fig. 4.3 and 4.4). This year, 1994, is accompanied by low magnitude, frequency, and duration rainfall and the time series also shows that the rainfall remains low without much fluctuation (Fig. 4.10). It is evident by comparing Figures 4.9 and 4.10 that rainfall is lower in 1994 than 1993 with much less fluctuation.

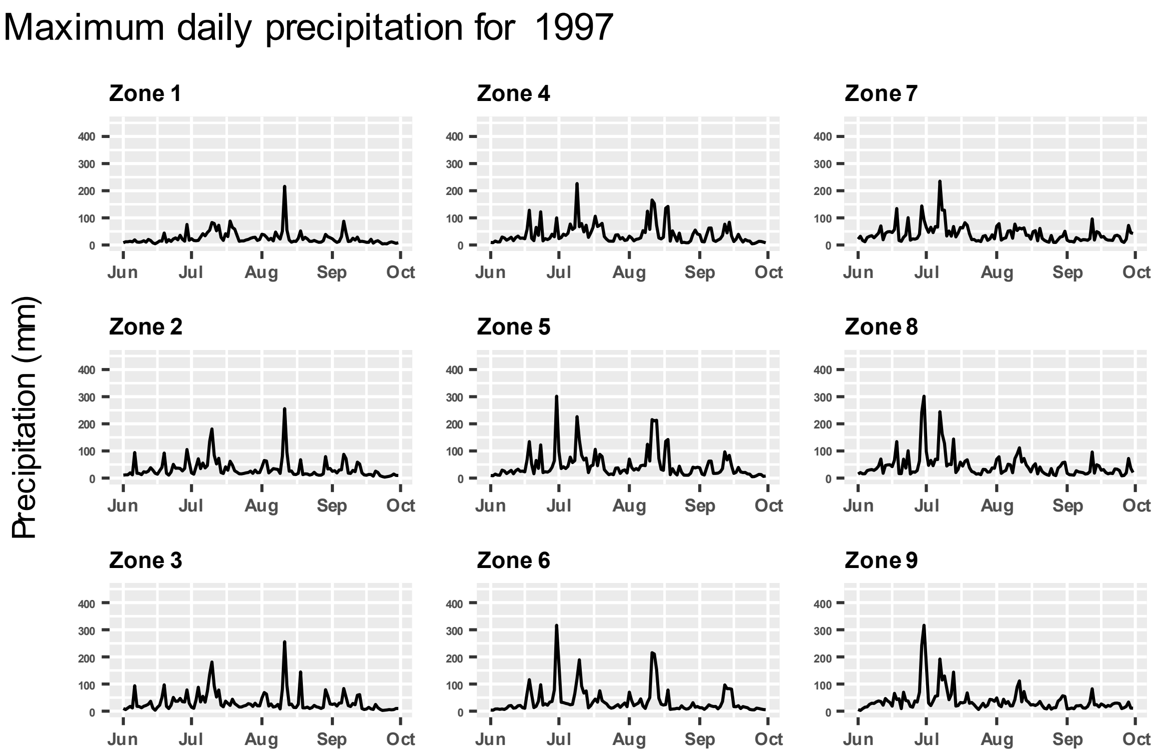


*Figure 4.12. Time series of daily maximum precipitation in 1997, in which year hazards are low.*

There is then a period when landslide and flood numbers are low throughout the monsoon with less than 12 landslides and less than 5 floods occurring in a single month in any zone. During this time, the rainfall metrics vary from high (426 mm) to low (30 mm) with little to no effect on hazard occurrence (Fig. 4.3 and 4.4). In 1997, for example, the time series plot (Fig. 4.11) shows that there are some high magnitude events reaching 317 mm in rainfall at the end of June in the Lowlands of the Gandaki (Zone 6). These high magnitude events are also seen in other parts of the Gandaki and throughout the Koshi basin (Zones 4, 5, 7, 8, and 9). Rainfall is then low throughout the monsoon in the Koshi basin with a high magnitude event of 112 mm in

August (Zones 7, 8, and 9) but there are some moderate events of maximum 255 mm in August in the Karnali and Gandaki basins.

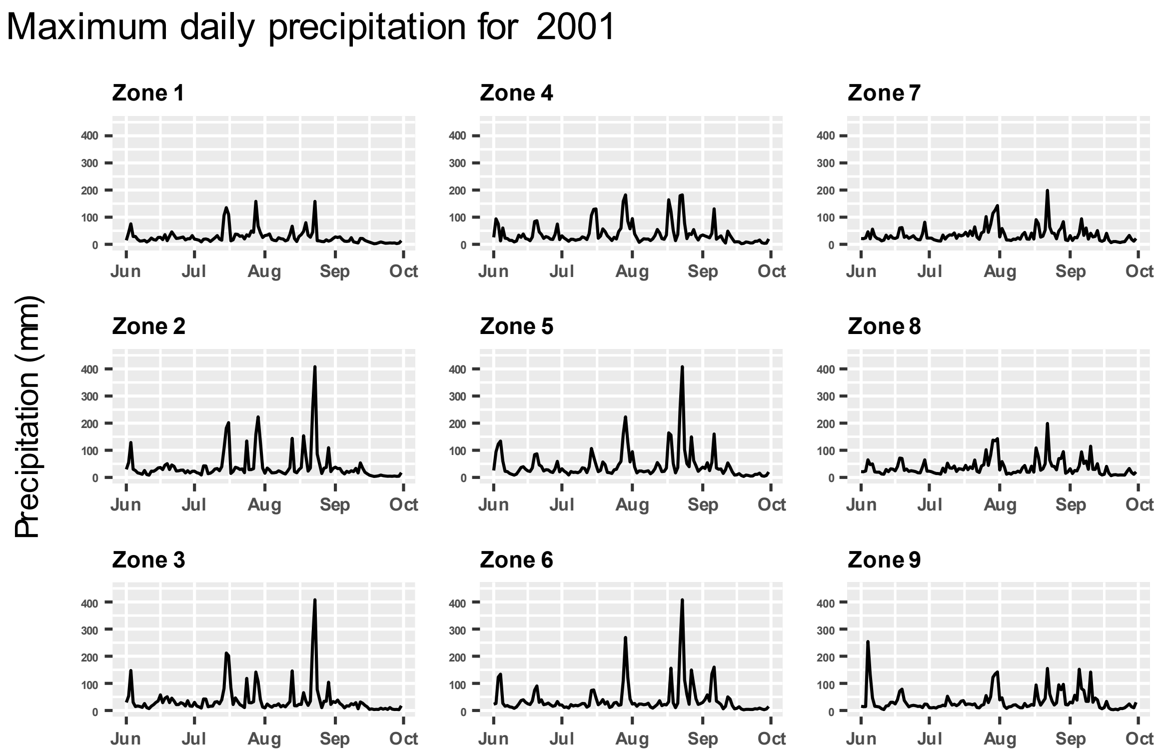


*Figure 4.13. Time series of daily maximum precipitation in 2001, in which year hazards are high.*

The only years when landslides and flooding are prevalent in all four months of the monsoon are 2000 and 2001. In 2000, landslides are relatively low in June and July with a maximum of 5 occurring. They are higher later in the monsoon in August with a maximum of 13 and are low in September returning to a maximum of 5 (Fig. 4.3). Floods occur throughout this monsoon, particularly in August with a maximum of 24, with moderate numbers of maximum 8 in June in the Karnali and Gandaki basins (Fig. 4.4). Rainfall magnitude is highest in June in 2000 with all values above 100 mm and low throughout the rest of that monsoon with a minimum of 61 mm (Fig. 4.5). Frequency and duration remain consistently low throughout the monsoon (Fig. 4.6 and 4.7).

There are moderately high numbers of landslides throughout the monsoon in 2001 with more in June and September than other years, whereas there are low numbers of floods in June, moderate flooding in July, relatively high numbers of floods in August and moderate numbers in September (Fig. 4.3 and 4.4). There is an extremely high magnitude rainfall event in mid to late August 2001 (408 mm) which hits the Lowlands and Middle Mountains of the Karnali and Gandaki (Zones 2, 3, 5, and 6) (Fig. 4.5). Frequency and duration still remain low (Fig. 4.6 and 4.7). The time series plot for this year shows that rainfall is low in June apart from an event of 254 mm in the beginning of the month in the Lowlands of the Koshi basin (Zone 9) (Fig. 4.12). Rainfall is higher in the Gandaki and Karnali basins (Zones 4, 5, 6, 7, 8, and 9) in July and August of this monsoon.

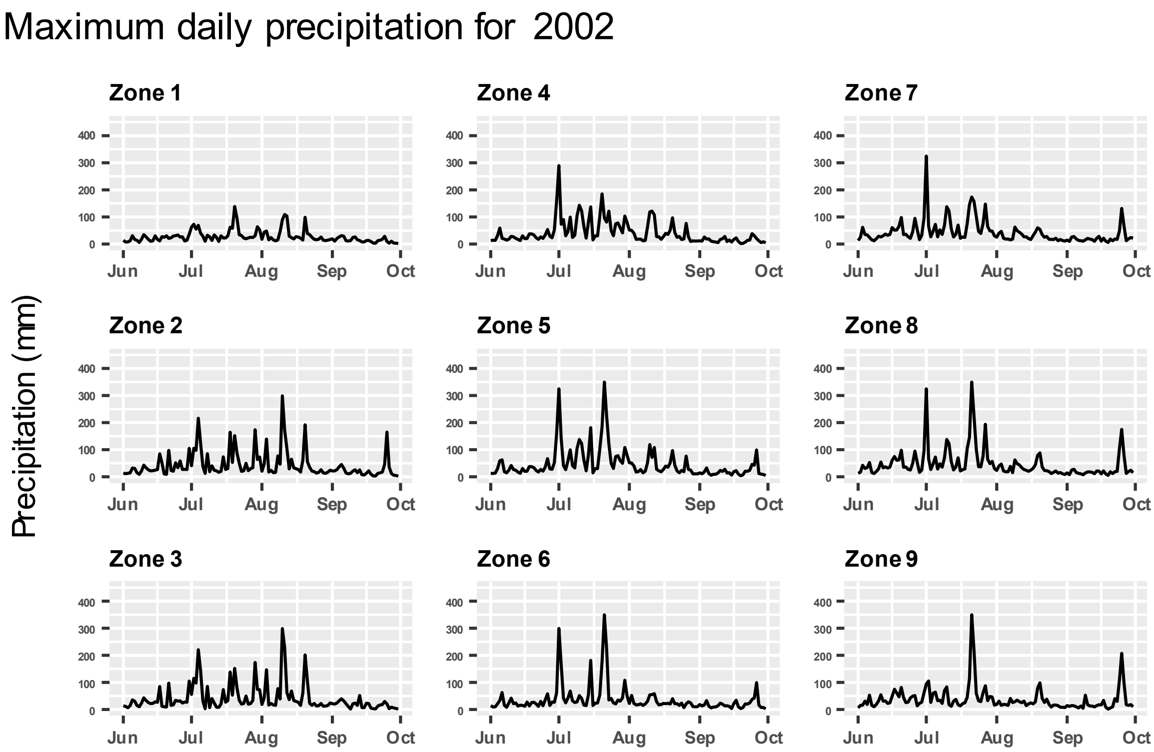


*Figure 4.14. Time series of daily maximum precipitation in 2002, in which year hazards are high.*

Extreme numbers of hazards occur in July 2002. Landslides reach 88 in the Middle Mountains of the Gandaki (Zone 5) and floods reach 63 in the Lowlands of the Koshi (Zone 9), their highest values in the data set. Flood numbers are also extremely high in the Middle Mountains of the Gandaki and Koshi reaching 63 (Zones 5 and 8) in July 2002. Landslide and flood occurrence are less in the Karnali river basin (Zones 1, 2, and 3) throughout that monsoon (Fig. 4.3 and 4.4). The rainfall magnitude is very high in the Gandaki and Koshi basins (Zones 4, 5, 6, 7, 8, and 9) reaching 350 mm in July 2002 (Fig. 4.5). Whilst the frequency and duration are very high, reaching a maximum frequency of 20 days and a maximum duration of 5 days throughout all zones in July of that year (Fig. 4.6 and 4.7). The rainfall is moderately high magnitude, frequent and of moderately high duration in the Middle Mountains and Lowlands of the Karnali (Zones 2 and 3) in August (Fig. 4.13). At the daily scale the rainfall in the Lowlands of the Koshi (Zone 9) appears to be low apart from one high magnitude event of 349 mm towards the end of July (Fig. 4.5, 4.6, and 4.7). The Middle Mountains of the Gandaki and Koshi, as well as the Lowlands of the Gandaki (Zones 5, 6, and 8) follow a similar trend to each other with high magnitude rainfall at the end of June and beginning of July followed by low rainfall the rest of the monsoon.

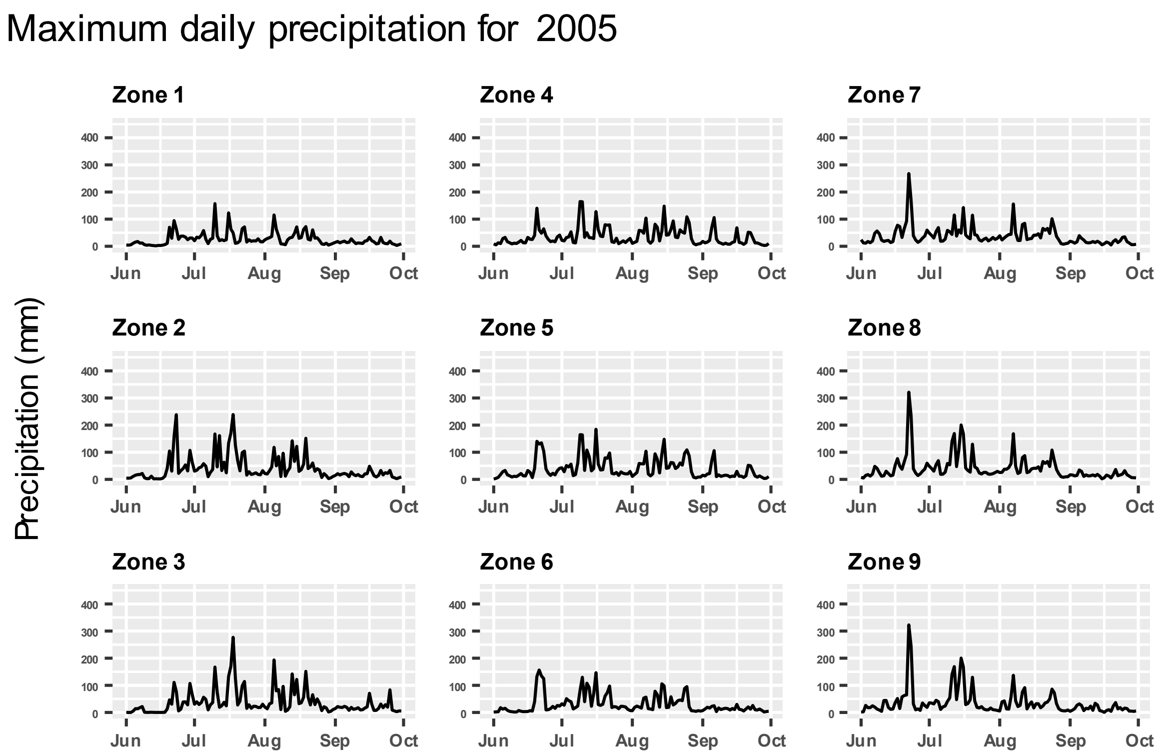


*Figure 4.15. Time series of daily maximum precipitation in 2005, in which year hazards are low.*

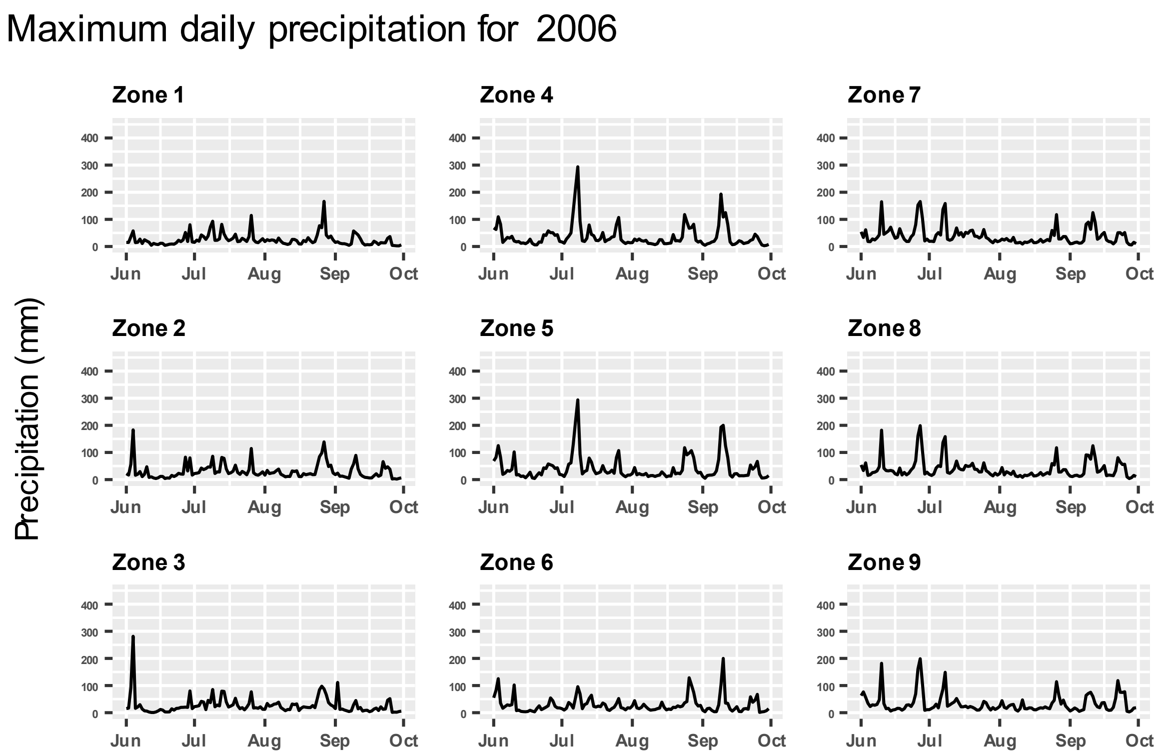


*Figure 4.16. Time series of daily maximum precipitation in 2006, in which year hazards are low.*

Low levels of landslides are spread throughout the monsoon in 2003 followed by 2004, a year in which there are very few landslides occurring at all. In 2003, flooding is high in August and relatively low in the other months. In July 2004, numbers of floods were at extremely high levels again (Fig. 4.3 and 4.4). There is an extremely high rainfall event in the Lowlands of the Karnali river basin (Zone 3) in July 2003 which also hits the Lowlands of the Gandaki basin (Zone 6), but to a lesser extent. The rest of that monsoon has only moderate magnitude events of maximum 248 mm. The entire Koshi basin (Zones 7, 8 and 9) is exposed to a rainfall event over 350 mm in July 2004 (Fig. 4.5). Frequency and duration are high in July 2003 with a maximum of 15 days above the 75$^{th}$ percentile and 6 consecutive days above the 75$^{th}$ percentile and in July 2004 maximum frequency and duration are 14 days and 10 days respectively (Fig. 4.6 and 4.7).

The subsequent years, 2005 and 2006 have relatively low levels of hazards until 2007, when there is moderate flooding in all four months accompanied by high frequency rainfall of maximum 20 days in July which remains moderate in August and September reaching a maximum of 13 and very high duration rainfall in July (12 days) and September (10 days) mostly in the Karnali basin (Zones 1, 2, and 3). In 2005, there is high rainfall in the Koshi basin (Zones 7, 8, and 9) in June followed by very low rainfall the rest of that monsoon. In 2006, the highest rainfall is in July in the High Mountains and Middle Mountains of the Gandaki (Zones 4 and 5) with low rainfall events in August and September. The years 2005 and 2006 have quite different time series plots (Fig. 4.14 and 4.15). In 2005, the rainfall is quite variable with many low rainfall events except a higher rainfall event in June in the Koshi basin (Zones 7, 8, and 9) (Fig. 4.14). On the other hand, 2006 has mostly low rainfall apart from some events which occur throughout the year in each zone (Fig. 4.15). This inconsistency can be seen in the

Lowlands of the Karnali basin (Zone 3) of June when there is a moderate event at the start not seen to the same extent in the rest of the Karnali basin or the Lowlands, there is a high magnitude event of 293 mm in July in only the High Mountains and Middle Mountains of the Gandaki (Zones 4 and 5) and the Koshi basin only has low events in rainfall occurring in June.

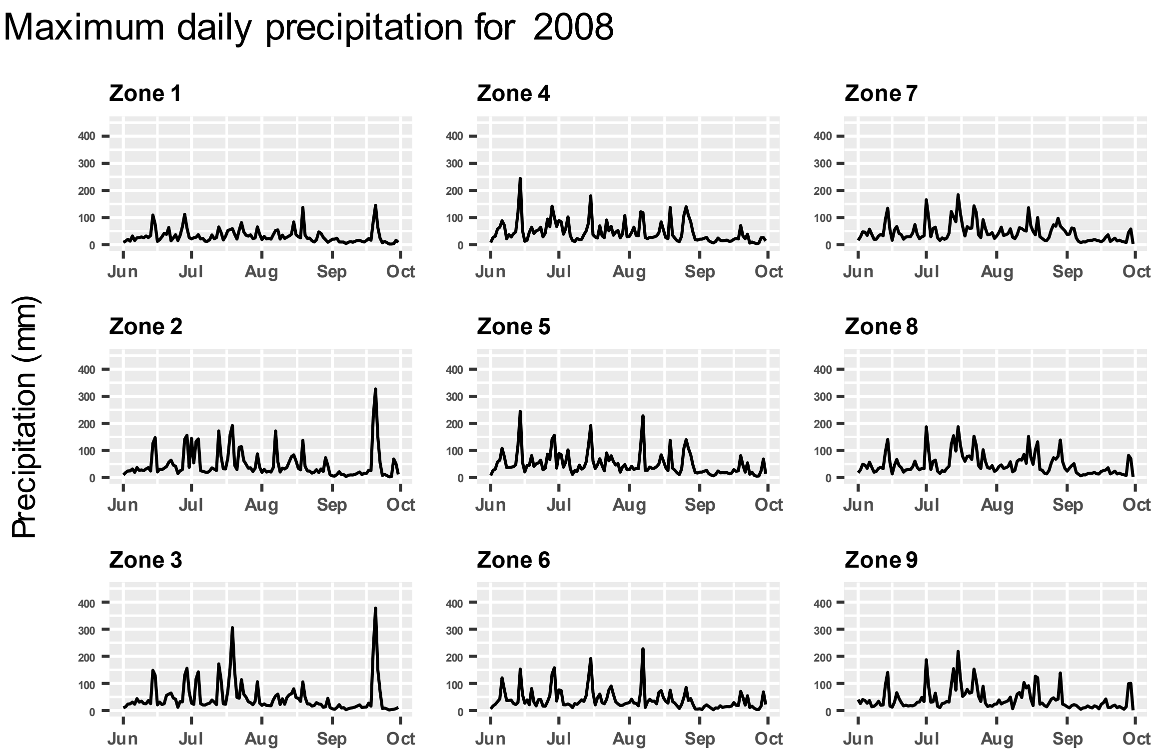


*Figure 4.17. Time series of daily maximum precipitation in 2008, in which year hazards are high.*

In 2008, there are a high number of landslides in the High Mountains and Middle Mountains of the Karnali river basin (Zones 1 and 2) and flooding is predominantly in those zones too (Fig. 4.3 and 4.4). In this year, there are more landslides in August whereas floods occur in July, August, and September (Fig. 4.3 and 4.4). There is an extremely high magnitude event across the Karnali basin in September 2008 of 378 mm. The time series plot shows that this event occurs towards the end of the month (Fig. 4.16). Rainfall frequency and duration also pick up in 2008 with moderate frequency in July and August and high duration rainfall in July in the Middle Mountains and Lowlands of the Koshi river basin (Zones 8 and 9) (Fig. 4.6 and 4.7).

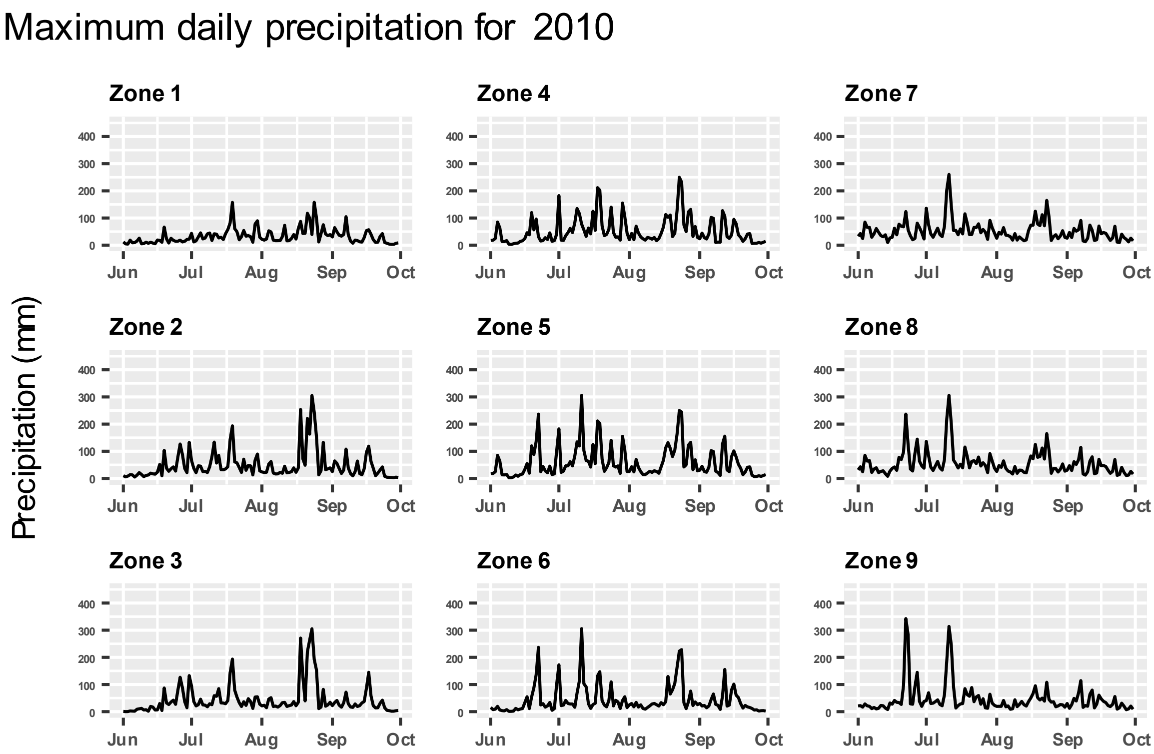


*Figure 4.18. Time series of daily maximum precipitation in 2010, in which year hazards are high.*

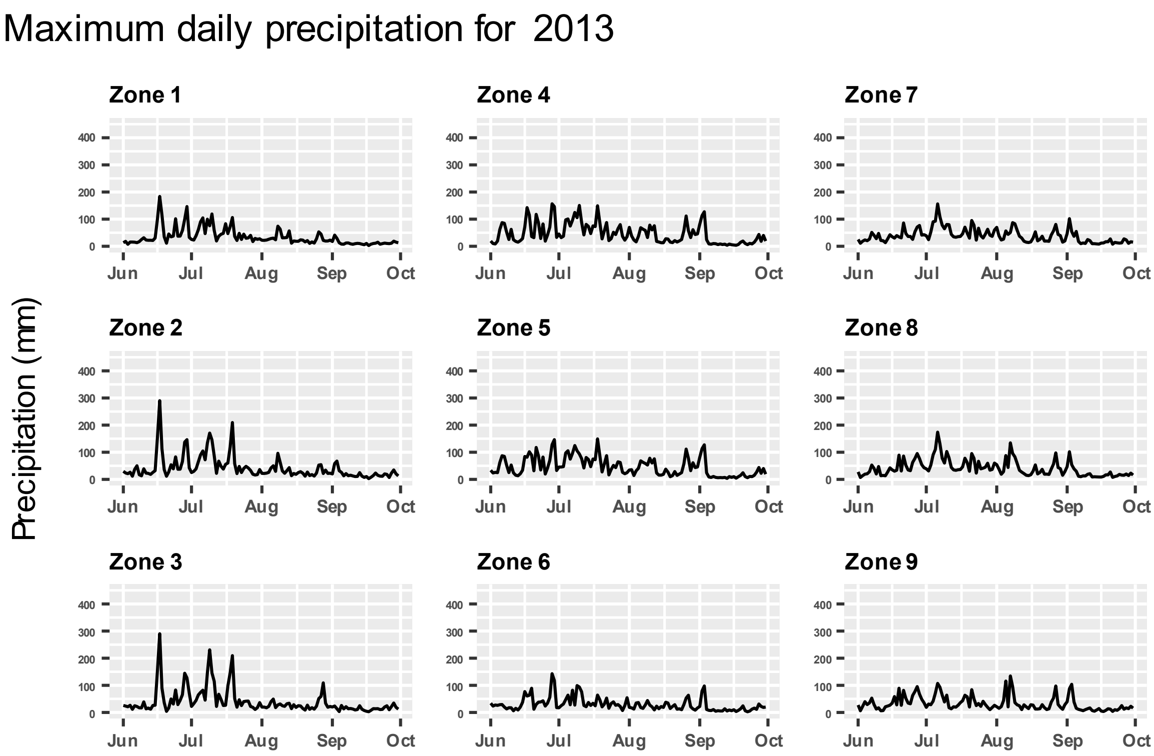


*Figure 4.19. Time series of daily maximum precipitation in 2013, in which year hazards are low.*

The final five years of the data set vary greatly in terms of hazard occurrence. The landslide and flood numbers are moderately low in 2009, followed by high levels in 2010 and 2011, then they are low in 2012 and 2013 (Fig. 4.3 and 4.4). The rainfall magnitude in 2009 is high in July whilst the frequency and duration are higher in August. In 2010, the rainfall magnitude is high in July in the Gandaki and Koshi basins (Zones 4, 5, 6, 7, 8, and 9) then high in August in the Karnali (Zones 1, 2, and 3) (Fig. 4.5). The frequency is high in July in all zones and moderately high in August. The time series plot supports this interpretation (Fig. 4.17). The rainfall metrics are low in 2012 and 2013 along with the hazard occurrence. The time series plot shows that there are moderately high magnitude rainfall events in June and July in the Karnali river basin (Zones 1, 2, and 3) but overall rainfall is very low in all zones throughout 2013 (Fig. 4.18). Precipitation is very low in the Lowlands of the Gandaki (Zone 6) in July and August with maximum rainfall only reaching 99 mm in August (Fig. 4.5).

### 4.4.3. The Southern Oscillation Index (SOI)

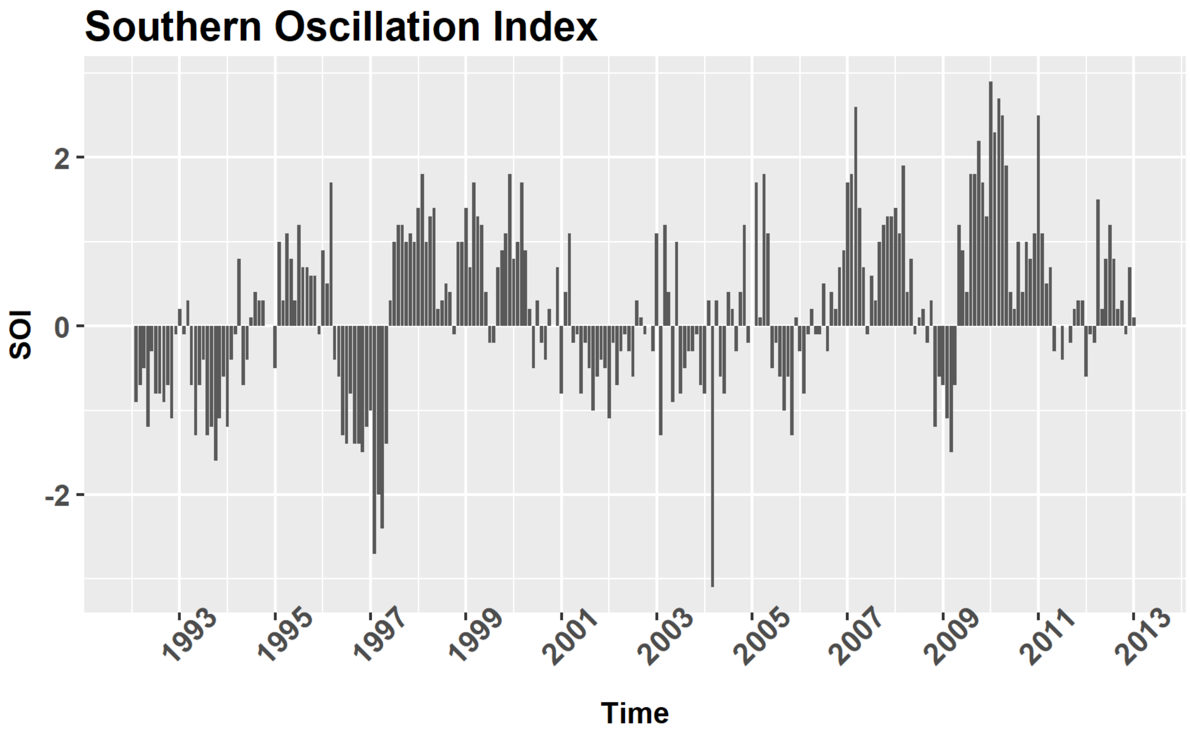


*Figure 4.20. Southern Oscillation Index (SOI) time series by month from 1993 to 2013. This data is downloaded from the National Centres for Environmental Information (NCEI).*

A time series plot of the SOI throughout the 20-year time period has been shown in Figure 4.19. The SOI is negative from 1993 to 1995 apart from certain months in 1994. There are positive values from 1995 to 1996 followed by negative values in 1997. There is a 2-year period of high positive values from 1998 to 2000. In 2001, the SOI is positive at the very beginning of the year but this changes to negative values throughout the rest of 2001 and into 2002 and 2003. There were mostly negative values in 2004 and 2005 with the highest negative value greater than -3 in February 2005, although there are some positive values later in that year. In 2006, values are positive in the early months then low negative. There are positive values in 2007 and 2008 until the end of 2009. The SOI reaches a positive value of 2.9 in December 2010. Values are all positive in 2011 with moderately high values at the beginning of the year, values fluctuate around 0 in the middle of the year, and a high value of 2.5 in

December. There are mostly low values fluctuating around 0 in 2012 and in 2013, values are mostly positive but range between -0.2 to 1.5.

Years in which there are positive values were 1995, 1996, 2001, 2006, 2007, 2008, 2009, 2010, 2011, and 2013. Few of these years correspond to years when landslides and flooding are high, namely 2001 and 2008. The only years in which positive SOI relates to high rainfall magnitude is 2008. High frequency rainfall occurs in 2007 when the SOI is positive and high duration rainfall occurs in 2008 when SOI is positive. Therefore, positive SOI values do not often correspond to high rainfall metrics or high hazard occurrence.

### 4.4.4. Landscape characteristics

The catchment properties (slope, river density, river gradient, land cover, and geology) were investigated in Chapter 3. Slope and river gradient increase on moving north through the Lowlands, Middle Mountains, and High Mountains whilst river density is highest in the Lowlands and decreases on moving north. This has major effects on the occurrence of water-related multi-hazards by modifying the slope stability and the rate of run off. The maximum rainfall is also affected due to the creation of an orographic barrier to rainfall and the funnelling of rainfall through valleys. The majority of land cover across Nepal is forest, however there is a high percentage of cropland and grassland in the Lowlands and the Middle Mountains and a high percentage of snow, glacier, and bare rock in the High Mountains. The different land cover types are responsible for changes in infiltration capacity and surface run off.

The geology of Nepal is very complex with predominantly metamorphic lithologies in the north and more sedimentary rocks further south. The presence of highly susceptible rock types and a number of major faults leads to a greater number of multi-hazards. Thus, landscape characteristics are key controls on the space-time occurrence of water-related multi-hazards.

### 4.4.5. Road density

The road network across Nepal from Open Street Map 2023 is displayed in Figure 4.21. The roads are categorised as primary, secondary, and tertiary roads, tracks, and motorway. Tracks vary from asphalt or heavily compacted to hardly visible and many are built informally. The road density calculations for these categories in each of the nine zones are shown in table 4.2.

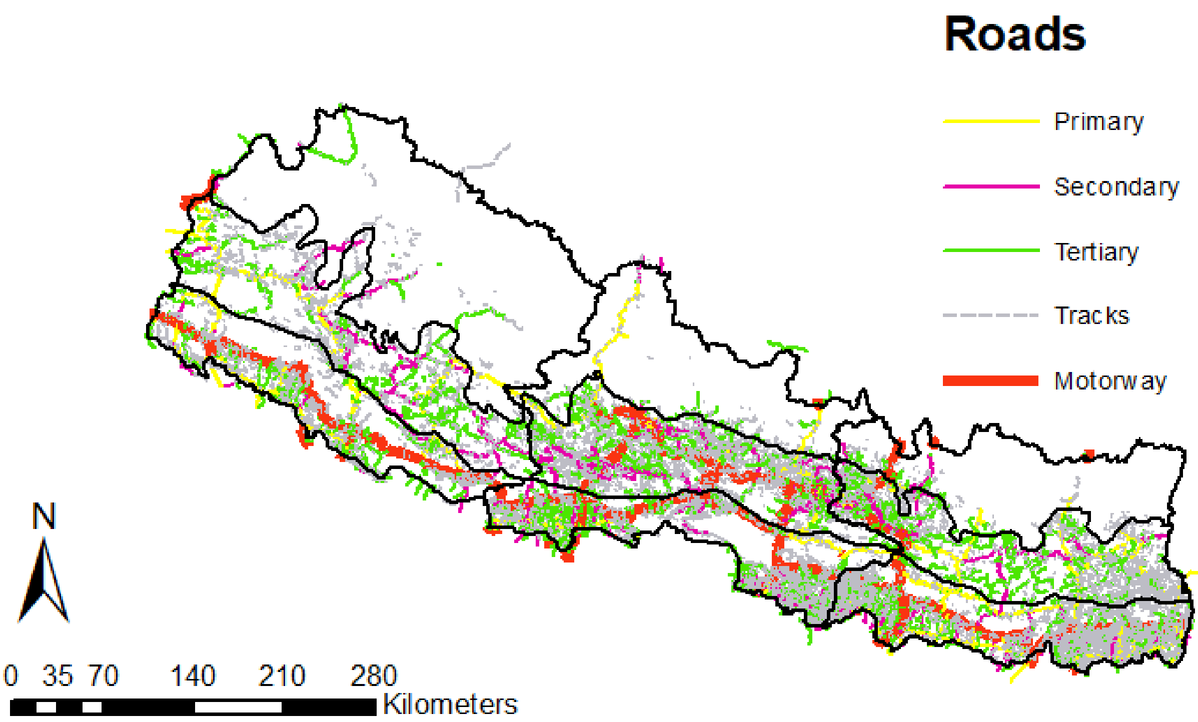


*Figure 4.21. Road network in Nepal from Open Street Map 2023 showing primary, secondary, and tertiary roads, tracks, and motorways.*

*Table 4.2. Road density, categorised as primary, secondary, tertiary roads, tracks, and motorways for the nine zones from Open Street Map 2023.*

| Zone | Primary ($km/ km^2$) | Secondary ($km/ km^2$) | Tertiary ($km/ km^2$) | Tracks ($km/ km^2$) | Motorway ($km/ km^2$) |
|---|---|---|---|---|---|
| 1: High Mountains of the Karnali | 0.002 | 0.007 | 0.01 | 0.021 | 0 |
| 2: Middle Mountains of the Karnali | 0.048 | 0.049 | 0.114 | 0.194 | 0 |
| 3: Lowlands of the Karnali | 0.048 | 0.012 | 0.116 | 0.287 | 0.035 |
| 4: High Mountains of the Gandaki | 0.019 | 0.003 | 0.023 | 0.039 | 0 |
| 5: Middle Mountains of the Gandaki | 0.032 | 0.098 | 0.23 | 0.528 | 0.043 |
| 6: Lowlands of the Gandaki | 0.03 | 0.052 | 0.197 | 0.45 | 0.042 |
| 7: High Mountains of the Koshi | 0.009 | 0.009 | 0.033 | 0.052 | 0.003 |
| 8: Middle Mountains of the Koshi | 0.059 | 0.058 | 0.233 | 0.38 | 0.013 |
| 9: Lowlands of the Koshi | 0.063 | 0.038 | 0.16 | 0.033 | 0.687 |

The highest density of motorway is in the Lowlands of the Koshi (Zone 9) with 0.687 km/ km2. The land in this zone is used primarily for agriculture and requires good road connections. The Lowlands of the Gandaki and Karnali (Zones 3 and 6) are also well connected for agricultural purposes. There is a high density of motorway in the Middle Mountains of the Gandaki (Zone 5), 0.04 km/km2, which connects the capital and area where most people live. The motorways do not pass through the High Mountains (Zones 1, 4, and 7). These mountainous zones are dominated by tracks which are usually informally built and may cause slope instability.

The primary, secondary, and tertiary roads provide connections throughout the country and are highest across the Middle Mountains and Lowlands. The highest density of tertiary roads is 0.223 km/km2 in the Middle Mountains of the Koshi (Zone 9).

The density of tracks is highest in the Middle Mountains of the Gandaki (Zone 5) with 0.528 km/km2 and is also high across the Middle Mountains of the Karnali and Koshi (Zones 2 and 8). The Lowlands are also well connected by tracks but this poses less risk of landslides as slope is low.

Hazard co-occurrence is highest across the Middle Mountains and central Gandaki basin (Zones 2, 5, 6, and 8) which are regions where road density is highest.

## 4.5 Discussion

The combination of these results give insight into hazard patterns and the mechanisms that interact with the landscape. There are three major findings from this analysis which will be discussed in this section with the inclusion of relevant literature.

1. Floods often occur later in the year than landslides indicating that antecedence could be more important in the occurrence of flooding.
2. Years when multi-hazards are high are followed by subsequent years when multi-hazards are low.
3. There is no clear evidence that one particular factor, such as the rainfall metrics, SOI, road density, land cover, geology, and other basin properties are driving the hazards therefore it must be a combination of hydrometeorology and catchment controls.

The spatial distribution of hazards can be seen in this analysis and supports Chapter 3 that landslides occur predominantly in the Middle and High Mountains, whilst floods are mostly in the Lowlands and there are high levels of co-occurrence in the Middle Mountains and the Lowlands of the Gandaki basin. In the current chapter we attempt to explain these patterns according to the rainfall metrics, SOI, and road density which were not looked at in the previous chapter.

There is a tendency towards more years in which landslides occur mostly in July whereas floods occur mostly in August. This could indicate a lag time between landslides and flooding, due to antecedent conditions being required for flooding or as a result of landslide damming river channels then breaking through later in the monsoon season causing large-scale flooding. The results of Bischiniotis et al., (2018) showed that most floods are preceded by relatively wet seasonal conditions when precipitation and evapotranspiration are high. Dahal (2012) concluded that landslides tend to occur only after a few days of the first monsoon rainfall. This indicates that antecedence is less important in landslide timing. However, Dai and Lee (2001) state that in most parts of the world antecedent rainfall and high magnitude rainfall are equally important for landslides.

Landslides and flooding usually follow a similar trend to one another, when landslides are high, floods are also high that year and vice versa. Adhakari (2013) stated that heavy floods were observed in the Nepal Terai in 1993, 1998, 2002, 2004, and 2008, and Roberts et al., (2021) found that landslide numbers were high in 1993 and 2002. The same years were found to have a particularly high number of floods and landslides in the present study, supporting the results. According to Adhakari (2013) and Pokhrel et al. (2009), the floods in 1993 were catastrophic causing up to 1,500 fatalities in central Nepal, the worst in its history. The study by Adhakari (2013), also mentions that the timing of landslides in the mountainous areas coincide with flooding in the Terai in the Karnali basin in 2008.

Roberts et al., (2021) found that there was strong path dependency in landslides in the central-eastern region of Nepal which would correspond to the Middle Mountains of the Gandaki and Koshi river basins. Thus, there is overlap between earlier landslides indicating that when one slope fails it acts as a catalyst for more landslides. This could explain the pattern in my results that years of high landslides are often followed by years with very few hazards, for example 1993 and 1994, and 2002 followed by the subsequent years. My study also found that in some cases there were consecutive years of high numbers of landslides, for example 2001 and 2002. These trends could be due to path dependency and the activation of slopes in one year (or more) leaving very few unstable slopes remaining and therefore a difference between the years of high landslides versus years with low numbers. The study of Roberts et al. (2021) and other literature does not include any effect this may have on flooding, if this was added it would lead to a more holistic multi-hazard approach.

The rainfall metrics (magnitude, frequency, duration, and antecedence) do not follow the same trend annually or spatially as each other. Years when there are high rainfall events do not coincide with years when there are lots of days above the 75$^{th}$ percentile or years when the number of consecutive days above the 75$^{th}$ percentile is higher. Zhang et al. (2019) also noted that rainfall characteristics do not necessarily follow the same trend as each other. The spatial distribution of the rainfall metrics is also different, for example rainfall magnitude tends to be higher in the Koshi basin and rainfall duration tends to be higher in the Karnali.

It was also found that years in which hazards are high were not necessarily associated with high rainfall metrics in most cases. However, Zhang et al. (2019) found that rainfall characteristics play an important role in controlling the occurrence of landslides in the Shaanxi Province, China. They argue that higher accumulated rainfall over a long duration has greater impacts on landslide occurrence than a high magnitude event. A large rainfall event is likely to overload the system irrelevant of the catchment properties and cause a great landslide and/or flood. However, such events are unlikely to cause repeated hazard events in that month. Bischiniotis et al., (2018) also found that high magnitude precipitation events do not always lead to hazard generation. Dahal (2012) noticed that a considerable number of landslides were triggered by continuous rainfall of five days or more, clearly demonstrating the importance of long duration rainfall on landslide initiation rather than short high intensity bursts.

On the other hand, Nayava et al., (2022) describe a single high intensity rainfall event in Nepal that occurred in July 1993 that was responsible for the widespread slope failures and flooding, while Jones et al., (2021) found that cloudburst storms in Nepal in 1993 and 2002 are known to have caused high numbers of landslides. These observations suggest that landslides could be driven by infrequent extreme rainfall events. However, in my results neither the magnitude, frequency, duration nor antecedence relate to years of high hazards This could indicate that there may be other driving forces of hazard occurrence. In Chapter 3 we found that the basin properties including land cover modify the rainfall and hazard occurrence.

Positive SOI values are normally associated with high rainfall (Shrestha 2000). Shrestha (2000) found that the SOI had a great influence on the South Asian Monsoon and therefore rainfall in Nepal. They state that years when there was more rainfall in Nepal were associated with years when the SOI was positive and years with deficient rainfall relate to years when SOI was negative. However, my results found that positive SOI values did not correspond to high rainfall metrics or high hazard occurrence. This difference could be as a result of my study only looking at the specific types of rainfall in defined regions. There is also a need for longer term records of the relationship between hazard activity and large-scale climate variability to reduce uncertainty surrounding hydrological response to future climate (Hannah et al., 2005).

It is known that informal road construction destabilises slopes during the rainy season (Vuillez et al., 2018). McAdoo et al. (2018) compared the distance between roads and landslides to determine if the spatial correlation implies causation. They found that landslides are more than twice as likely to occur within 100 m of a road due to over steepened slopes, poor water drainage and poor debris management. The results in section 4.4.5 show that the zone with the highest road density is also the zone with the highest number of landslides. Overall, the highest road density tends to be in the fertile land of the Lowlands where there are a low number of landslides and high numbers of floods. This area has the majority of the highways. McAdoo et al., (2018) found that it is not the highways that are necessarily the problem but the rural gravelled roads that are more likely to be responsible for landslides because these roads are poorly engineered. Therefore, it is important to look at my results for the tracks which have a relatively high density in the Middle Mountains and where there are the highest number of landslides. Vuillez et al., (2018) investigated land use/land cover changes in a case study through the period 1979-2016. They also found that roads are influencing slope stability. I cannot imply causation in my study because I have analysed at a much broader scale, therefore this study provides a different perspective to the study of Vuillez et al., (2018). To make a stronger link to causation, it would be valuable to investigate changes in road density and landslides at close proximity to roads through time. Thus, roads must be looked at more closely in future work and if informal road building is the main modifier of rainfall driven hazards, then there is a pressing need for reconsideration of the current rural access to reduce informal road building and ensure the building of roads in a more sustainable way.

## 4.6. Conclusion

This chapter has examined space-time interactions between hydrometeorology and catchment controls on water-related multi-hazards. From my analysis in Chapter 3, I know that multi-hazards vary according to hydrometeorology, basin properties, land cover, and geology. Here, a more refined methodology was followed based on the multi-hazard framework in Chapter 2 to zoom in further to understand the associated processes. This study has examined the occurrence of water-related multi-hazards in relation to rainfall characteristics, atmospheric circulation, and road density. The findings of my study are that there are multiple potential factors contributing to multi-hazard occurrence, high magnitude rainfall is not the only driver of multi-hazards, antecedent conditions may be more important in the occurrence of floods than landslides, activation of landslides change the landscape dynamic and may cause more or less in subsequent months and years, and road building may be a causative factor for landslides.

In summary, there is a combination of natural and anthropogenic factors contributing to the occurrence and co-occurrence of multi-hazards. This knowledge must be combined with an understanding of social vulnerability and investigation of social-economic drivers to develop a place-based approach to multi-hazard research. This will be the focus of Chapter 5.

# Chapter 5 - Social vulnerability to multi-hazards: elaborating the 'People and Place' pillar

## 5.1. Abstract

This chapter argues that new insights into social vulnerability to water-related multi-hazards arise from adopting what is described as a place-based approach. Chapter 2 proposed an interdisciplinary framework that highlighted the importance of combining analysis on both the physical and social aspects of water-related multi-hazards. The physical aspects of water-related multi-hazards were addressed in Chapters 3 and 4 which are linked to social vulnerability and place in the current chapter. A narrative review was used to define and conceptualise social vulnerability and evaluate the current analytic approaches. This was valuable in identifying gaps in the literature, including that the key drivers of social vulnerability are still poorly understood, and that current assessments of social vulnerability do not adequately capture space-time variations and, crucially, fail to recognise the critical importance of the relationship between physical environment and social relations in propagating multi-hazards. This chapter shows that while social vulnerability manifests locally – notably through differentiated coping strategies of people to address natural hazards among other place-based processes – it propagates from the intertwining of social and physical processes across multiple scales. To explore these relations in more detail, and drawing on the literature in human geography, three different conceptualisations of place are identified: (1) as a site close to others in space-time, (2) a specific location imbued with particular norms and attributes, and (3) a setting where external networks interact with local attributes to yield change (events). The place-based approach

advanced here argues for greater consideration of social vulnerability deriving from everyday experiences of multi-hazards among people in specific places and the historic experiences of communities living there who have direct experience of their effects.

## 5.2. Introduction

Water-related multi-hazards have major repercussions on the development opportunities of populations by causing large scale economic damage and fostering social vulnerability (Twigg et al., 2003). Continual repair and recovery from damages may increase the capacity to cope, but invariably it restricts the ability to progress and develop sustainably (Sudmeier-Rieux et al., 2012).

The second chapter of this thesis presented a framework for understanding water-related multi-hazards in a sustainable development context. The framework has two pillars for structuring analysis: one that is focused on physical processes termed 'Hazards and Environment', and the other associated with social and geographic processes termed 'People and Place'. The third and fourth chapters tackled the first pillar, the physical processes associated with water-related multi-hazards, their interrelationships, and how they relate across scales and levels. Ultimately these pillars coalesce to recommend a place-based approach to multi-hazard prediction and modelling.

This chapter builds on Chapter 2 by returning to the second pillar, focused on 'People and Place'. To recap, this pillar flags the key importance of social vulnerability as a theoretical lens for clarifying the intertwining between people, communities, and the physiographic and climatological drivers of multi-hazards in the places they live. The chapter has two aims. First is to clarify my thinking behind the conceptual underpinning of the 'People and Place' pillar. Secondly, I consider the added value that the place-based approach of this pillar can bring to advancing the field of multi-hazard studies. My argument is made according to the following stages.

First, I undertake a narrative review of the social vulnerability literature to clarify current understandings of this concept and analytical approaches to it, focused chiefly on studies conducted across Nepal. I also use the 2021 census of Nepal to evaluate proxies for social vulnerability and how they intersect. This uses empirical evidence to discover what characteristics makes certain communities, individuals or regions more or less vulnerable to hazards. The narrative review and proxy analysis enable the identification of limitations with existing work, which are addressed in the latter sections of the chapter.

Secondly, noting these limitations arise partly because social vulnerability is still a relatively new field of study, I argue that these shortcomings can be addressed in two ways. First is by deeper consideration of the scaled construction of social vulnerability within multi-hazard-prone countries/regions, in particular how social vulnerability needs to be understood simultaneously as discourses, practices, and lived experiences that cut across different scales of resolution (i.e., national, regional, and local). I then contend closer examination needs to be made at the local scale of the interrelations between social capabilities to address multi-hazards in places, the social and economic conditions of people in those places, and how these combine with the physical drivers of relevant multi-hazards.

I exemplify this argument by drawing on the physiographic-climatological processes examined in Chapters 3 and 4 to show how this iterative relation plays out practically. On this basis, I argue the concept of place offers the crucial nexus where the processual-relational aspects of multi-hazards are brought together as the different everyday lived practices and experiences of people and communities in relation to multi-hazards that make them more/less vulnerable to these processes. Finally, I sketch out potential benefits that arise from a place-based approach, that go above and beyond the argument set out in Chapter 2.

I conclude that social vulnerability is crucial in understanding how multi-hazards are experienced by people in place, but nonetheless is still poorly understood. This arises from its multi-dimensionality, in terms of being constituted from numerous physical, social, economic, and environmental factors and influences (Birkmann, 2006).

Moreover, social vulnerability is dynamic over time, and, as already noted, its effects are experienced differently depending on the scale at which it is analysed. For example, at the national scale, social vulnerability is often framed as a public policy problem to be 'solved', with importance attached to quantitative data for its measurement such as number of fatalities and financial costs of infrastructure lost. By contrast at sub-national scales, social vulnerability is usually portrayed as a narrative or a practice by prevailing social or political interests, such as local district administrations or community representatives. And at the individual scale, personal experience of multi-hazards and individual and community capacities to adapt – factors that are inaccessible nationally, regionally, and sometimes even locally - are crucial to understanding social vulnerability.

At these micro-scales, community groups and individuals are likely to have numerous different coping strategies in relation to multi-hazards they encounter. Coping strategies for social vulnerability are related to social capitals (e.g., trust, reciprocity, social ties, and obligations) and social networks of relations that people and communities can call upon in emergencies, the physical resources available to them to address multi-hazards, and whether these are accessible when needed. I conclude that social vulnerability requires a 'portfolio' approach to its theorisation, and the use of complementary qualitative and quantitative methods to track its outcomes and effects.

Having outlined the Chapter structure and argument in the first section, I set out the methodology used to undertake the narrative review of publications on vulnerability in Nepal and the analysis of various proxies.

The Covid-19 pandemic starting in 2020 prevented community level fieldwork on social vulnerability which was planned originally. This would have been informed by the narrative review that follows.

## 5.3. Narrative review of social vulnerability literature in Nepal

This section presents a narrative review of social vulnerability to multi-hazards. I review publications along three axes; definitions of social vulnerability, conceptualising social vulnerability, and the approaches employed to analyse them. I then critically analyse these definitions, concepts, and approaches, with the aim of identifying the differences, similarities, gaps, and limitations, which are discussed in the second section.

Narrative review methods are aimed at identifying and summarising what has previously been published, avoiding duplicates, and identifying new study areas through critical review, synthesis, and representation (Ferrari, 2015). I use these methods here to critically appraise literature related to the vulnerability of multi-hazards in Nepal. I focus particularly on strategies for understanding social vulnerability to multi-hazards. The narrative review differs from the bibliometric analysis performed in Chapter 2 in that the literature sample was not analysed according to year published, geographic origin or term co-occurrence, but is similar in that I applied a standardised, reproducible search strategy. This was as follows.

In the data collection phase, peer-reviewed publications were identified using key word searches and screened according to selection criteria. I searched for articles published in English between October 2001 and October 2021 using Web of Science, Scopus, and Google Scholar. I used multiple key word searches using every combination of the words ‘vulnerability’ or ‘social vulnerability’ and ‘multi-hazards’ or ‘landslides’ or ‘floods’ and ‘Nepal’. Vulnerability and social vulnerability are often used interchangeably throughout the literature. The search identified 72 articles after removing duplicates. The titles and abstracts of these papers were then screened to remove irrelevant studies and references to theoretical work were added manually, including Birkmann 2006, Blaikie et al. 1994 and Cutter, 1996.

After the screening stage, 34 articles were chosen to be synthesised in the discussion of our narrative review, of which 20 were case studies in Nepal. The reason for focusing on literature based in Nepal was that this is directly relevant to the work of the thesis. Another approach would be to analyse the totality of the literature, but this would give considerable bias towards a European or North American centred perspective which is not an appropriate lens for this study. However, where appropriate we have pulled through some review literature based in high income countries (HICs), for example Cutter et al. 2003, to provide wider transferability.

The sampled literature is analysed below, based on the following research questions: (a) What is vulnerability – how is it defined? and (b) What theoretical and empirical approaches are used in the sample to evaluate vulnerability to multi-hazards?

In addition to this analysis of the literature, I use the 2021 census of Nepal to evaluate empirical evidence on how three proxies of social vulnerability make defined zones more or less vulnerable to hazards. The nine zones used are the same as those used in the previous two chapters. I triangulate my findings with recent literature which show how the proximate vulnerability to hazards in Nepal can be intensified by socio-economic factors.

## 5.4. Definitions and theoretical concepts of social vulnerability

Vulnerability is an intrinsic characteristic of a system, also known as “the internal side of risk” (Birkmann, 2006: 16). This means that the conditions of the exposed element or community at risk are seen as core characteristics of vulnerability; this view is seen in nearly all conceptualisations of the term in the sample. Blaikie et al. (1994: 8) and Cutter (1996: 529) give broad definitions of vulnerability: "being prone to or susceptible to damage or injury", and "the potential for loss" respectively. Both refer to loss in terms of fatalities and infrastructure damage. These definitions form the basis of vulnerability definitions that are widened in papers in the sample around factors such as susceptibility, coping capacity, exposure, risk, and resilience (Table 5.1). Blaikie et al. (1994: 8) also offers a more refined working definition of vulnerability “the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard.”

*Table 5.1. Interpretation of the definitions of social vulnerability concepts in the context of natural hazards combined from the sampled literature.*

| Concepts | Definition |
|---|---|
| **Susceptibility** | The likelihood of being influenced by a hazard (Blaikie et al., 1994). |
| **Sensitivity** | The condition of being affected by factors leading to harm (Giri et al., 2021). |
| **Coping/adaptive capacity** | Capability to deal with damage during a hazardous event by alleviating or containing the impact or by bringing about effective relief (Birkmann, 2006). |
| **Exposure** | The state of people, assets, livelihoods, and ecosystems present that could be affected by a hazard (Giri et al., 2021). |
| **Risk** | The probability of occurrence of a hazard (Birkmann, 2006). |
| **Resilience** | The capacity of a person, household, or other aggregate unit to reorganise, recover, and transform in response to a hazard (Cieslik et al., 2019). |

Vulnerability can be seen as dualistic, with susceptibility on one side, and coping capacity on the other (Birkmann, 2006). For example, Chaudhary et al. (2021) emphasise coping in their approach to understanding vulnerability, stating that "vulnerability is commonly understood as the susceptibility of a system/community, arising from its inability to cope with the adverse effects of various types of change" (Chaudhary et al., 2021: 3). Similarly, Giri et al. (2021: 2) attribute vulnerability to the inability to cope: “vulnerability arises due to a lack of capacity to cope and adapt”. Oven (2009: 46) describes coping strategies as “measures that act directly upon damage during an event by alleviating or containing the impact or by bringing about effective relief”. This social response to hazards is a crucial concept in conceptualising vulnerability.

Widening the concept further, vulnerability can be seen as multi-layered. Schilling et al. (2013) describe vulnerability as a function of “exposure”, “sensitivity”, and “adaptive capacity”. Adaptive capacity is used interchangeably with coping capacity in this conceptualisation. The sample draws attention to several factors specific to Nepal that are crucial in limiting adaptive capacity, including high levels of poverty, weak governance, and a history of conflict (Schilling et al., 2013; Sugden et al., 2014).

A system is sensitive to detect or respond when exposed to a hazard and exposure is the state of people, assets, livelihoods, and ecosystems present that could be affected (Giri et al., 2021). These are in keeping with the established conceptualisation of vulnerability from risk governance in which risk = hazard x exposure, where risk is the likelihood of occurrence of a hazard (Cutter, 1996; Gautam, 2017). Weichselgartner (2001: 1) similarly relates vulnerability to the characteristics of “hazard, exposure, preparedness, prevention, and response”.

Vulnerability and resilience are also closely interrelated concepts that are discussed in the sample (Cutter et al., 2008). As noted above, vulnerability focuses on the situation or the system's susceptibility to hazards, whereas resilience is determined by the capacity of a system to reorganise and recover (Schilling et al., 2013). Ran et al. (2020: 1) define resilience as "the ability of a system, community, or person, to prepare, cope with, recover, and adapt to a hazard or hazardous event". In a study by Cieslik et al. (2019: 4) resilience is defined as "bouncing forward" as opposed to "bouncing back". This challenges the idea of returning to the original system state after a hazardous event and proposes instead building adaptive capacity for positive, potentially transformative, change.

Guillard-Gonçalves and Zêzere (2018) assert vulnerability has multiple dimensions, stating that it is dynamic, intrinsic, scale-dependent, and site-specific. In their paper, 'dynamic' refers to vulnerability varying over time and to the interaction between physical and social attributes and characteristics. These authors bring scale into their conceptualisation, arguing that vulnerability varies within societies from the national to the individual. Moreover, they contend that vulnerability is site-specific, requiring approaches based on individual places and timings. These authors also highlight the perspective that vulnerability is based on historical and cultural processes in stating that social vulnerability is the "predisposition or susceptibility of social groups in the context of a disaster" (Guillard-Gonçalves and Zêzere, 2018: 1). Wang et al. (2021: 1559) also highlight the political and socio-economic qualities of vulnerability by stating that social vulnerability is "determined by the pre-event socio-demographic and economic conditions".

Similarly, Aksha et al. (2019: 1) draws attention to the way in which physical and social scientists describe vulnerability differently: “physical scientists ... tend to conceptualise vulnerability in terms of the likelihood of occurrence of a specific process and associated impacts on the built environment”, whereas “social scientists tend to define vulnerability as a set of social, economic, and demographic factors that coalesce to determine people’s ability to cope with stressors”. For them, vulnerability is a product of social relations: “vulnerability ultimately manifests as the stratification and unequal impacts among different groups of people across space” (Aksha et al., 2019: 1). This foregrounds space as a dynamic quantity in constructing vulnerability, suggestive of the diverse ways in which space can be used, perceived, experienced, and produced by people and communities to change vulnerability processes and outcomes (Sugden et al., 2014).

Cutter et al. (2003: 243) characterise vulnerability according to the individual/group and their situation, stating that “vulnerability is most often described using the individual characteristics of people (age, race, health, income, type of dwelling unit, and employment)”. Thus, some groups in society are more prone to damage, loss, and suffering than others (Blaikie et al., 1994).

Aksha et al. (2020) argues for a multidisciplinary perspective to conceptualising vulnerability, bringing together physical process with socio-economic context. They add the dimension of biophysical vulnerability, in which the occurrence of hazard or damage incurred is due to the hazard action upon the system. They argue this should be measured in terms of the physical sensitivity of the landscape to specific hazards in terms of variables including elevation, slope, and land use. Here vulnerability is conceived as both a physical risk as well as a social response. This conceptualisation is useful as it contextualises the social systems and components that are more/less vulnerable in relation to the physical environment.

Hazards, however, cannot be blamed on nature alone. Raju et al. (2022: 1) state that “disasters occur when hazards meet vulnerability”. This argues that natural hazards become disasters as a result of social vulnerability which is often created by unplanned urbanisation, systemic injustice, and marginalisation. The role of human activity in increasing the likelihood and exacerbating the impacts of hazards must be recognised in understanding social vulnerability.

Rigg et al. (2016: 1) broadens the vulnerability concept to include physical, social, economic, environmental, and institutional features, by stating it is “a pre-existing state of marginality or exposure, whether social (e.g., caste or gender relations), physical (e.g., isolation), environmental (e.g., unimproved land or water resources) or economic (e.g., lack of market engagement or access to financial resources)”. This definition describes some of the causes of vulnerability and emphasises the need for sensitivity to different individual vulnerabilities within social groups.

Chaudhary et al. (2021) conceptualise vulnerability according to the knowledge, interpretation, and experience of people. These authors argue that exposure of individuals is shaped by their cultural values, beliefs, attitudes, and worldviews. Posch et al. (2019) also argue for the importance of considering values and worldviews in determining human actions/responses in the event of a hazard. These components particularly at the individual scale are important for the mitigation or exacerbation of vulnerability.

Dilshad et al. (2019: 1) put vulnerability in context by relating it to various conditions at multiple scales and time frames. They define social vulnerability as "a set of conditions of people that is derived from the historical and prevailing social, economic, cultural, environmental, and political context along with understanding future scenarios". This contextual approach foregrounds the way in which these factors induce differential capacities and sensitivity to hazards. However, their definition does not consider how more marginal or excluded individuals and groups in the "prevailing social, economic, cultural, environmental, and political context" may be more vulnerable to hazard exposure, and hence more likely to experience negative effects. In turn, this suggests social vulnerability needs to explore the intersections between social identities around for example ethnicity, gender, class, caste, age, and education, all of which are profoundly important in Nepal in determining individual and group access to resource allocation and hazard exposure (Sugden and de Silva, 2014; Sugden et al., 2014). Intersectional approaches could thus potentially lead to deeper and more holistic understandings of vulnerability.

Much of the sampled literature considers the interrelation between vulnerability and poverty (Devkota, 2013; Giri et al., 2021).  Rigg et al. (2016: 1) for example describes vulnerability as "forward looking and predictive", whereas poverty is a state of being, stating that vulnerability is "why individuals or households might be prone to poverty". They also introduce the concept of precarity in terms of development, in which vulnerability is an inherited form of livelihood exposure, yet precarity is produced (Rigg et al., 2016).

*Table 5.2. Definitions of social vulnerability from the literature and interpretations.*

| Definition of vulnerability | Interpretation | Reference |
|---|---|---|
| **“the internal side of risk”** | This describes vulnerability as an intrinsic characteristic of a system or element at risk. | Birkmann (2006: 16) |
| **“being prone to or susceptible to damage or injury”** | This is a basic commonplace definition which describes vulnerability in terms of susceptibility or likeliness. | Blaikie et al. (1994: 8) |
| **“the potential for loss”** | Broad definition which is developed to include the susceptibility of social groups or society at large to potential losses from hazard events. | Cutter (1996: 529) |
| **“multidimensional concept that helps to identify those characteristics and experiences of communities (and individuals) that enable them to respond to and recover from environmental hazards”** | The characteristics mentioned are used as variables to quantify social vulnerability in social vulnerability indexing. | Cutter et al. (2003: 257) |
| **“the susceptibility of a system/community arising from its inability to cope with the adverse effects of various types of change”** | This definition combines both susceptibility and coping capacity. | Chaudhary et al. (2021: 3) |

| | | |
|---|---|---|
| **“a propensity to be adversely affected and assessed through the IPCC framework based on the three dimensions of vulnerability – exposure, sensitivity and adaptive capacity”** | This widens the concept and describes vulnerability as multi-layered. | Giri et al., (2021: 2) |
| **“vulnerability ultimately manifests as the stratification and unequal impacts among different groups of people across space”** | This indicates that a holistic understanding of the social, economic, and political contexts between spaces is required to understand vulnerability. | Aksha et al. (2019: 1) |
| **"a pre-existing state of marginality or exposure, whether social (e.g., caste or gender relations) physical (e.g., isolation), environmental (e.g., unimproved land or water resources) or economic (e.g., lack of market engagement or access to financial resources)”** | This definition describes some of the causes of vulnerability. | Rigg et al. (2016: 1) |
| **“a set of conditions of people that is derived from the historical and prevailing socio-economic, cultural, environmental, and political contexts along with understanding future scenarios”** | This brings in time as a dimension by mentioning historical, prevailing, and future scenarios of vulnerability. | Dilshad et al. (2019: 1) |

In summary, the definitions and conceptualisations of vulnerability differ within the literature (Table 5.2). While these definitions do not conflict, they do vary in terms of the scale, unit, time, space, place, and processes deemed as important in understanding vulnerability. Similarly, they depict vulnerability arising from different hypothesised interactions between social and physical systems – sometimes emphasising the importance of intertwining of the physical and the social, while others assert one or other system as dominant. Other components included in the definitions include risk, sensitivity, and adaptive capacity. Nonetheless, while the sampled literature draws attention to different components and factors, there are core attributes in all accounts, namely ‘exposure’ and ‘susceptibility’. An overarching definition would incorporate all these components. One such example is Birkmann's (2006: 17) attempt to classify vulnerability based on a concentric circle model, showing “key spheres of vulnerability” (Fig. 5.1).

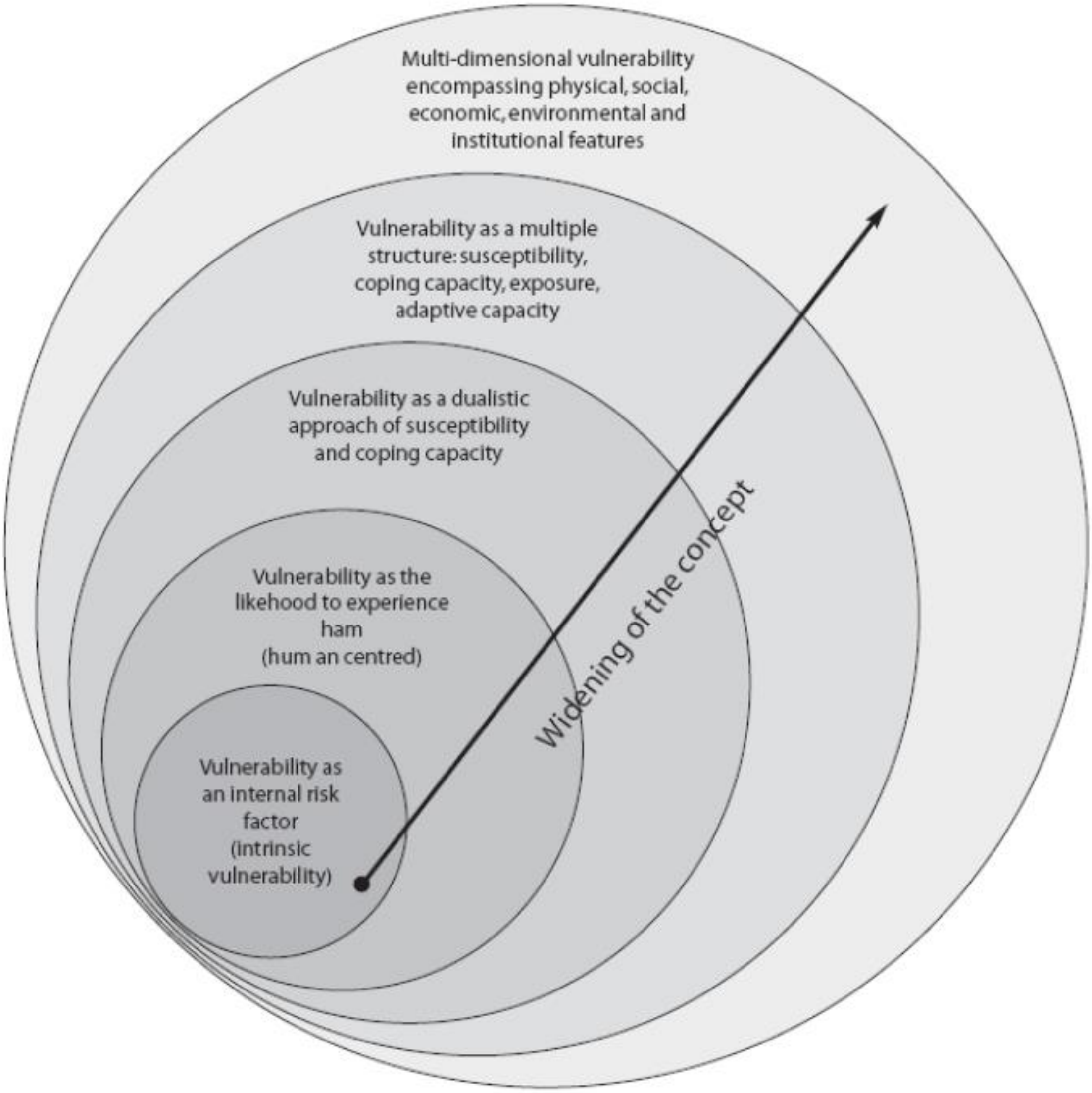


*Figure 5.1. Concentric model of the vulnerability concept according to the "key spheres" of vulnerability (Birkmann et al., 2006: 17).*

Having discussed the different definitions provided in these studies, the chapter now moves on to consider the different methods used in the sampled literature to evaluate vulnerability.

## 5.5. Theoretical and empirical approaches to evaluating vulnerability to multi-hazards

The focus of this section is to analyse methods of evaluating social vulnerability, predominately in Nepal. Many of the approaches use the connections between factors such as population, gender, and education. These intersect to make certain communities, individuals, and regions more or less vulnerable to hazards.

The sampled literature showed marked differences in theoretical and empirical approaches to evaluating vulnerability to multi-hazards. Broadly these can be split into work using quantitative risk-hazard and qualitative social constructivist approaches. On the quantitative risk hazard side, studies seek to measure vulnerability using numerical indices (Gautam, 2017; Guillard-Gonçalves and Zêzere, 2018). Indices of social vulnerability were first developed by Cutter et al. (2003) based on criteria such as education, wealth, age, and gender. A strength of this approach is that it enables the quantification of vulnerability spatially and allows comparisons between case study examples that can help identify socio-economic vulnerability drivers (Wang et al., 2021). Many quantitative social vulnerability indices have been developed and applied globally in different hazard settings, with the indicators modified and expanded to give high spatial resolution accounts of vulnerability (Aksha et al., 2019; Giri et al., 2021).

Indices can be 'weighted' (i.e., specific factors given additional importance) using methods such as expert judgement, analytical hierarchy process (AHP), principal component analysis (PCA), and multiple regression models. They can also be combined using additive and/or multiplicative equations. PCA reduces the number of social vulnerability indicators into a smaller number of components by grouping similar variables (Aksha et al., 2019). AHP is used to integrate various variables and determine their importance, weighting, and rank (Aksha et al., 2020). Multiple regression models are used to test whether and how vulnerability to hazards is associated with the social economic indicators (Samir, 2013).

The index approach can be elaborated further through qualitative or quantitative research methods, depending on the scale and the framing. Qualitative research methods include interviews, focus group discussions (FGD), and participant observation, such as those used in Bista (2019), and Sudmeier-Rieux et al. (2012). These data provide for a more nuanced and complex understanding of people and place, including their cultural values and beliefs (Posch et al., 2019). Quantitative methods include household surveys/questionnaires and the use of secondary sources of data from available literature, historical records, and governmental reports and surveys. For example, the most recent census is often used, as is the case in Aksha et al. (2019) and Gautam (2017). These methods provide empirical research findings on specific social characteristics that mitigate or exacerbate social vulnerability. Table 5.3 describes the strengths and weaknesses of some of the approaches used in Nepal to evaluating social vulnerability in the sample literature.

*Table 5.3. The strengths and weaknesses of approaches to evaluating social vulnerability in Nepal from the sampled literature.*

| **Reference** | **Data collection** | **Strengths** | **Limitations** |
|---|---|---|---|
| Aksha et al. (2019) | Census | Broad scale visual understanding. | Not based on empirical data. |
| Gautam (2017) | Census | Broad overview of vulnerability and the key drivers. | Does not consider the spatial variation of vulnerability within districts. |
| Giri et al. (2021) | Household surveys | Captured minor differences to compare spatial units. | Small-scale study. |
| Devkota (2013) | FGD and interviews. | Gives an in-depth view of people's perceptions and experiences. | Can only be performed at a small-scale. |
| Chaudhary et al. (2021), Gentle et al. (2014), Rigg et al. (2016) Samir (2013), and Sudmeier-Rieux et al. (2012) | Household surveys, interviews, FGD, and participant observations. | Quantitative results were validated by in-depth qualitative data. | Data very limited in scale. |
| Aksha et al. (2020) and Wang et al. (2021) | Hazard mapping, census, government records and key informant interviews | Combined both physical and social processes. | There were some limitations in the availability and spatial resolution of data. |
| Dilshad et al. (2019) | Hazard mapping, socio-economic mapping, FGD, key informant interviews, and multi-stakeholder workshops. | Combined physical processes and social demographic data.<br>Combination of data collection methods. | Small-scale study. |

Aksha et al. (2019) applied and modified the social vulnerability index to quantify vulnerability to multi-hazards in Nepal. In this study, 39 social indicators were used, with PCA applied to distil these variables. The social vulnerability index was calculated using an equal weighting and additive approach in the absence of empirical or justifiable evidence for weighting components differently (Aksha et al., 2019). To evaluate social vulnerability spatially, each spatial unit was given a social vulnerability index score which was mapped using ArcMap. Gautam (2017) also used social economic variables derived from census data to map social vulnerability. They used a purely arithmetic method based on score-based social vulnerability mapping at the district scale, evaluating all 75 districts of Nepal. These methods have their advantages in giving a broad overview of vulnerability and the key drivers, but as they are not based on empirical data, they do not give a clear picture of how individual and household vulnerability varies.

Household level surveys are also used to assess social vulnerability quantitatively. Giri et al. (2021) used household level questionnaires to statistically assess social vulnerability of four informal settlements in Nepal. They used a social vulnerability index based on selected indicators to assess three elements of vulnerability: exposure, sensitivity, and adaptive capacity. This approach captured the minor differences across different units furthering our understanding of the vulnerability system (Giri et al., 2021).

Community and key informant interviews form the basis of a number of vulnerability assessments (Schilling et al., 2013). This method is important to understand the coping strategies of the affected people. Devkota (2013: 1) aimed to assess flood vulnerability in Nepal 'through the eyes of the vulnerable'. They used FGD and household interviews in two communities to identify and test the drivers of vulnerability. This gave an in-depth evaluation of people's perception and experience but is limited in only being able to be applied at the small scale.

Household surveys/questionnaires are often coupled with interviews, FGDs and participant observations in a mixed method approach to evaluate social vulnerability. Chaudhary et al. (2021) used indicators taken from household surveys/questionnaires to give percentages of population at risk of hazards. They then used in-depth interviews, FGDs, and participant observation to validate and triangulate their findings. This allowed them to indicate which sub-groups of the population were more vulnerable than others and give reasons for this. Gentle et al. (2014) also used a mixed method approach in a study using social vulnerability indices. Household surveys/questionnaires were used to estimate a well-being status determined by variables such as food production, employment, and social status. Again, qualitative methods, including interviews, FGDs, and participant observation, were used to give a more complex understanding of the people and place.

Samir (2013) conducted household level surveys to obtain data to run a regression model to test whether floods and landslides were related to various social economic indicators. The findings were then validated by conducting in-depth interviews with stakeholders at various levels. This combination of methods differs from the solely quantitative methods described previously at the national level and differ from those carried out using household surveys alone at the individual and community scale. The mixed method approach is also adopted in Sudmeier-Rieux et al. (2012), Rigg et al. (2016), and Samir (2013). The advantage of these mixed methods approaches is that the reliability and validity of research is increased.

Some authors combine both physical and social processes in their analysis. Aksha et al. (2020), for example, combined a multi-hazard risk map from remotely sensed imagery and a social vulnerability map from social vulnerability indices in a case study location in Nepal. The social data was obtained from census, government records and key informant interviews. For this analysis, they used statistical methods and the AHP to determine the relative importance of each variable. This method was valuable because it combined both physical and social processes and created a holistic understanding of multi-hazard risk. However, there were some limitations in the availability and spatial resolution of data (Aksha et al., 2020). Similarly, Wang et al. (2021) related social vulnerability to hazard intensities using mapping techniques and quantitative secondary sources.

Dilshad et al. (2019) also combined physical risk assessment with social vulnerability indices. They blended quantitative methods from secondary sources with qualitative data collected to interpret vulnerability in four river basins. This case study used a variety of methods including hazard mapping, socio-economic mapping, FGDs, key informant interviews, and multi-stakeholder workshops to yield a comprehensive evaluation of vulnerability.

Designing and implementing social vulnerability indices is clearly an emerging field. However, as these examples show, there are some limitations to their use. The inconsistency of data collection methods and scales of vulnerability resolution within the literature makes it difficult to compare indices. For example, it is hard to make comparisons between different spatial scales and the activities of affected households (Wilson, 2019). Data availability may determine the selection of variables, and where these are not the same comparative studies are not possible. Another limitation is that they do not always consider the physical characteristics of hazards, such as hazard intensities (Wang et al., 2021).

To conclude this section, the approaches developed and used in the sampled literature are chiefly social vulnerability indices that are broadly compatible, if not directly comparable. Variation in their formulation between studies seems to occur less because of conceptual differences, than as a result of the differing empirical contexts these studies engage with. Nonetheless, I noted a number of shortcomings in the sampled literature as follows.

First is that, while many studies reflect on vulnerability arising from the interrelation between social and environmental factors, they do not reflect further on *how* it is constituted from the intertwining of social and physical environmental processes. Most studies are more concerned with developing more accurate/sensitive ways of representing vulnerability through indices, than with conceptualisation. Secondly, there is a lack of consideration of whether/how different indices are comparable, and hence whether they give insight into a single multi-faceted cross-scale vulnerability process or refer instead to different nested scaled processes that together make up vulnerability. Thirdly, there is widespread recognition among authors that vulnerability is socially constructed, i.e., it is defined through human social interactions (Aksha et al., 2019; Gautam, 2017). However, with notable exceptions (Sugden and de Silva; Sugden et al., 2014), few studies follow up on the implications of this insight – namely that if this is so, vulnerability understandings vary among different groups, as well as geographically – notably with scale. Vulnerability is thus a nested scaled process with associated set of practices and scale-variant outcomes. But so far, the literature tends to conflate these scale-variant constructions and dynamic processes as singular static vulnerability outcomes.

On the basis of the preceding analysis, I argue valuable insights can be gained into social vulnerabilities to multi-hazards in Nepal by working with vulnerability proxies, including population, literacy rate, and proportion of men living abroad. In the next section, empirical evidence from the 2021 census of Nepal will be used to apply these proxies to the nine case study zones used in the earlier chapters.

## 5.6. Proxies for Social Vulnerability in Nepal

Nepali communities grapple with multifaceted vulnerabilities that stem from a number of different factors including the nation's high poverty rates (Gentle et al., 2014), substantial reliance on migrant remittances (Al-Haddad et al., 2022), vast socioeconomic inequality between ethnic and caste groups (Clement & Sugden, 2021), rapid urbanization across unstable terrain (Thapa et al., 2020), and low levels of literacy and education (Nakano et al., 2020). These factors intersect to amplify disaster impacts along existing fault lines of vulnerability (Cutter et al., 2003).

In the previous two chapters, Nepal has been divided into nine zones to compare the space-time distribution of water-related multi-hazards and the related influences (Fig. 5.2). In this section, proxies will be discussed and a representative district falling within one of the nine zones will be selected to assess the levels of social vulnerability related to that proxy. The proxies chosen as examples are population density, literacy rate, and proportion of men living abroad. This allows for contextual understanding of distinct landscapes, socio-economic conditions, cultural factors, and local capacities in different regions.

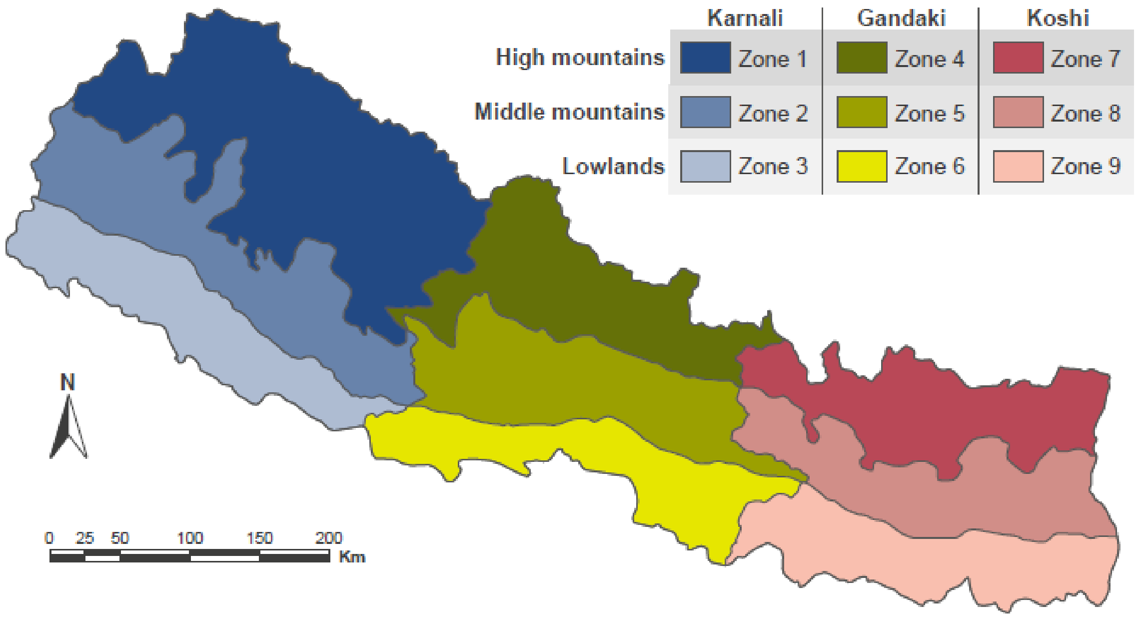


*Figure 5.2. Nepal delineated by nine natural zones defined by drainage basin and physiography. These are the same nine zones that are used in Chapters 3 and 4.*

Population is a proxy for social vulnerability which must not be overlooked because a place with a high population density equates to more people, property, and businesses at risk of suffering from the adverse impacts from natural hazards (Gall, 2013).

Literacy rate is important because it affects peoples' ability to process hazard warnings and to inform themselves and their families about hazard prevention measures. Those who are uneducated may not know which Non-Governmental Organisations (NGOs) and government agencies can provide assistance and when they are able to approach them.

Number of males living abroad can be used as a proxy for economic disadvantage as it shows the number of households relying on remittances coming back from abroad. It also reduces household capacity to respond to emergencies as there are less people with skills, expertise, and labour to draw upon. This puts a greater burden on those who are left to cope.

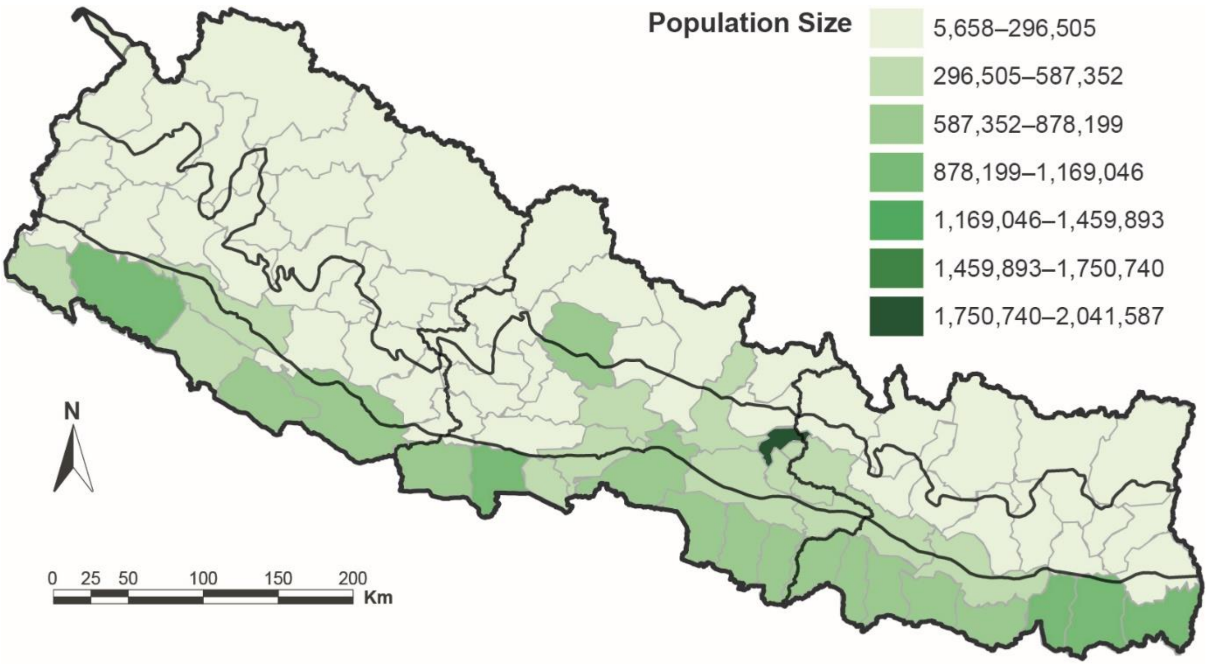


*Figure 5.3. Map of population by district. This map was taken from the National Population and housing census of Nepal* (GoN, 2021).

The total population of Nepal is 29,164,574. This is unevenly distributed with most people living in the capital, Kathmandu, which is in the Middle Mountains of the Gandaki (Zone 5) which has a population of 2,041,587 (Fig. 5.3).

The Lowlands (Zones 3, 6, and 9) have the highest population with 904,666 in Kailali which is in the Lowlands of the Karnali (Zone 3) 1,121,957 in Rupandehi in the Lowlands of the Gandaki (Zone 6) and 1,148,156 in Morang in the Lowlands of the Koshi (Zone 9). The reason for many people living in the Lowlands is that there is fertile land for agriculture however as found in Chapters 3 and 4 these areas are exposed to flooding and are often at high risk. Excluding Kathmandu, the population size in the Middle Mountains varies from 56,789 in Rukum in the Middle Mountains of the Karnali (Zone 2) to 600,051 in Kaski in the Middle Mountains of the Gandaki (Zone 5). Chapters 3 and 4 found that the Middle Mountains had the highest number of landslides and flooding, the range in rural population is large and indicates varying levels of vulnerability. The High Mountains have a low population ranging from 5,658 in Manang in the High Mountains of the Gandaki (Zone 4) to 262,624 in Sindhupalchok in the High Mountains of the Koshi (Zone 7). The High Mountains are exposed to a high number of landslides but as there are very few people living in these zones it is likely that social vulnerability is low. The major issue with high population per unit area is greater likelihood of exposure to hazards but it also reveals pressure on resources and access to services.

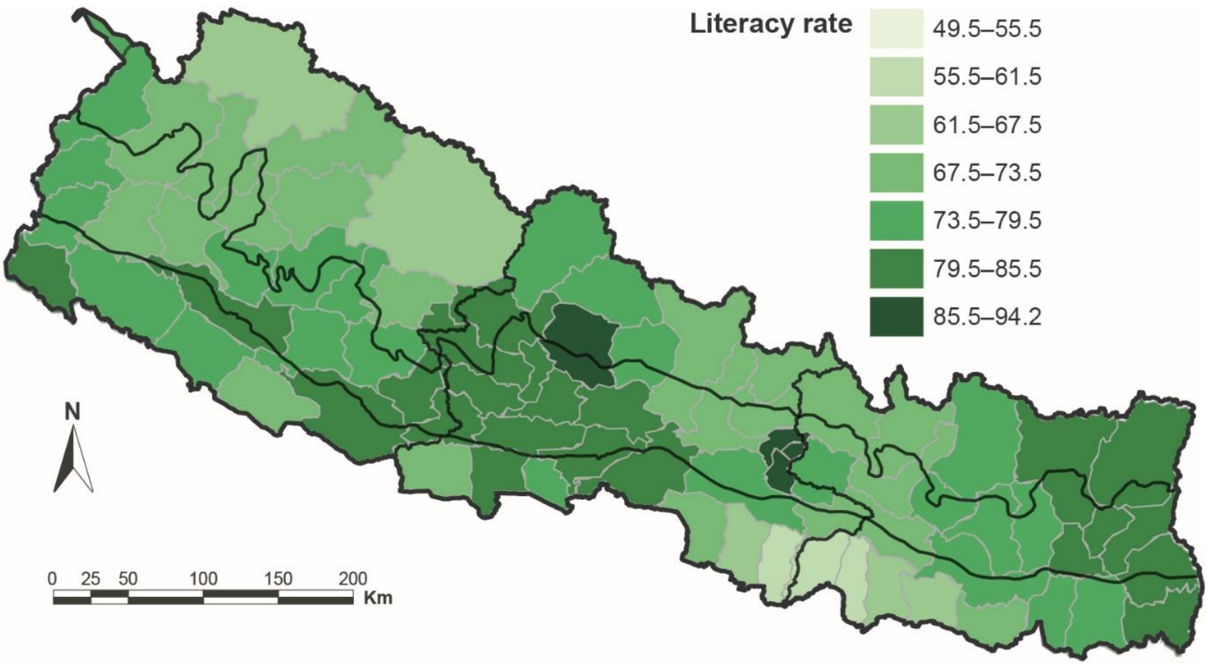


*Figure 5.4. Map of literacy rate (%) by district. This map was taken from the National Population and housing census of Nepal* (GoN, 2021)*.*

Literacy rate is a proxy for education which affects how people are able to gain assistance and adapt to hazards (Fig. 5.3). Communities or households without education may become isolated and be at a disadvantage (V. P. Pandey et al., 2019).

Literacy rate is highest in the capital, Kathmandu, where it is 89.2%. It is also high in Kaski, 87.7%, and Laitpur, 88.1%, which are all districts within the Middle Mountains of the Gandaki (Zone 5). Therefore, although number of hazards are high in these zones people are less vulnerable than people in the Lowlands where there is frequent flooding. There are a few districts in the Lowlands of the Gandaki and Koshi (Zones 6 and 9) where literacy rate is low, for example Rautahat with 57.8%, Sariahi with 60.3%, and Mahottari with 59.8%.

Education is important for evaluating social vulnerability because where literacy is low people will find it difficult to access resources and help in an emergency (Poshan et al., 2013). Analysing a flood event, Gentle et al. (2014) found communities with higher illiteracy had more difficulty understanding written warnings and rebuilding efforts were slowed by the locals inability to interpret policy guidance for reconstruction. Developing rural education and accessible early warning systems may strengthen resilience to multi-hazards (Petal, 2006).

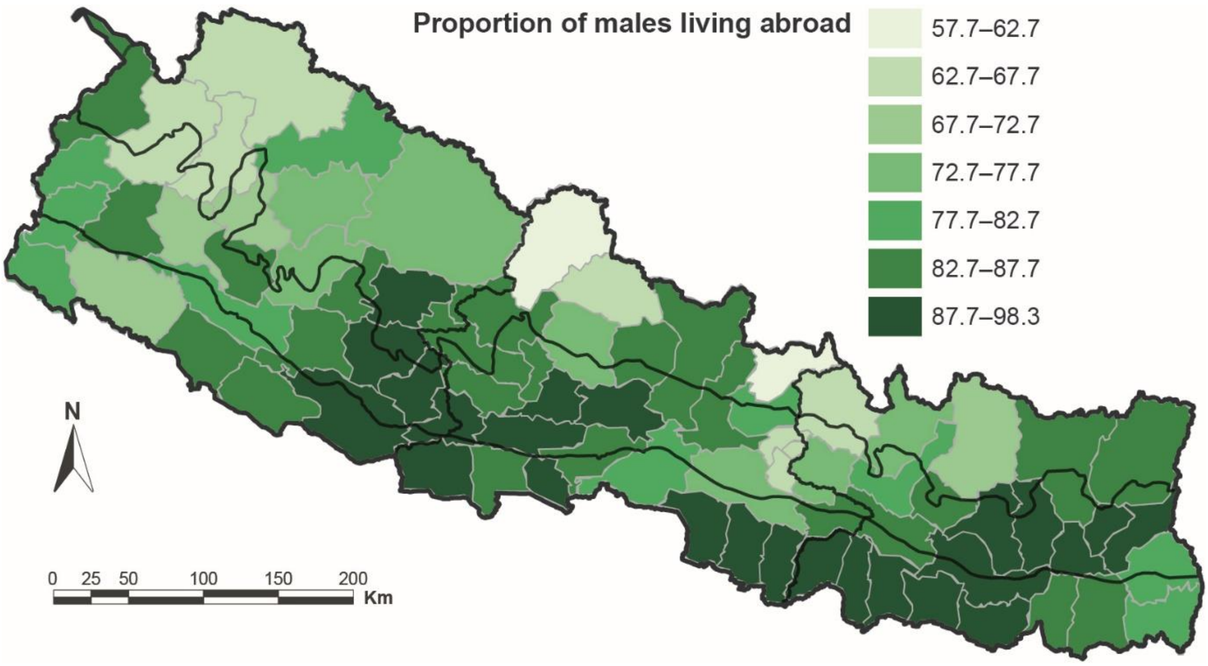


*Figure 5.5. Map of percentage of males living abroad. This map was taken from the National Population and housing census of Nepal* (GoN, 2021).

The districts with the highest proportion of males living abroad are predominately in the Lowlands and Middle Mountains of the Gandaki and Koshi (Zones 5, 6, 8, and 9).

These include Sirahi with 98.3% (Zone 9) and Khotang with 90.0% (Zone 8). The high number of hazards in these zones combined with these figures increases the vulnerability of populations. There is a low percentage of males living abroad in the High Mountains, for example Humla, 64.6% (Zone 1), Mustang 61.9% (Zone 4), and Rasuwa 57.7% (Zone 4). However, using number of males working abroad as a proxy can be problematic and potentially misleading. There is high seasonal out-migration to India from Humla and other districts in the far west of Nepal which is not captured in government figures (Gautam, 2017; Hoermann and Kollmair, 2009). Therefore, vulnerability may be underestimated in these zones. This is a limitation of using national data as it often does not reflect the complexity of the situation at district or household level.

Due to a lack of economic opportunities many households rely on remittances from migrant workers, creating “absentee households” devoid of working labour. Therefore, number of males living abroad can be used as a proxy for economic disadvantage (Fig. 5.4). Households with less people find it more difficult to respond because there is more to do for those who are left (Simkhada et al., 2017). Addressing chronic poverty and creating local employment may reduce migration dependence and lower the risks of displacement of people during disasters.

High illiteracy rates, dependence on migrant remittances in the absence of local livelihood opportunities, and extensive poverty intersect with the country’s challenging topography and rapidly growing population to exacerbate the impacts of multi-hazards and make some populations more severely affected than others.

Analysis also reveals that lower caste groups shoulder more adverse landslide and flood consequences due to social marginalisation, exclusion from decision making activities, and residence in exposed rural areas (McAdoo et al., 2018). Poorer citizens hold the least disaster preparedness knowledge and resources for hazard mitigation or recovery, resulting in cascading economic damages following events (Gentle et al., 2014). Rather than affecting all populations equally, multi-hazards disproportionately impact marginalized groups, particularly low-income communities, communities of colour, disabled populations and the elderly (Osipian, 2016).

The concept of “intersectionality” recognizes that socio-economic factors often overlap and converge in ways that exponentially increase vulnerability (Kuran et al., 2020). Applying an intersectional lens in multi-hazard research in Nepal sheds light on how hazards disproportionately impact individuals and communities.

There are several case studies conducted across Nepali communities that have examined the complex social factors that shape social vulnerability to multi-hazards and show how social vulnerability to hazards in some parts of Nepal are intensified by socio-economic factors.

Sharma et al. 2022 assessed village vulnerability to flooding in Nawalparasi district using indicators like population size, literacy rate, and occupation types. They found that population size alone did not determine flood vulnerability however when overlaid with other factors like high illiteracy and widespread poverty, these large populated villages were much more vulnerable than smaller villages with higher literacy and greater economic means.

Likewise, Thapa (2021) found higher population density in Kathmandu correlated with greater urban flood vulnerability only when combined with low-income levels and low education attainment.

The compounding effects of marginalisation become evident through intersecting different proxies. Gaire et al. (2015) showed remittance dependence intersecting with poverty and social exclusion in remote mountain areas amplified disaster impacts. Dalit communities studied by Jones and Boyd (2011) faced magnified flood vulnerability due to intersecting caste, class and gender marginality. Samir (2013) addressed the issue of differential vulnerability to natural hazards at the level of village communities in Nepal. The results showed that there were less human and animal deaths in households that were wealthier and better educated.

Intersectional studies of urban flooding revealed socioeconomic status, gender, and age shaped flood vulnerabilities in the Kathmandu Valley (Kumar et al., 2019). In another study it was found that the size of landholdings and potential to diversify had an impact on vulnerability to flooding in Western Nepal (Sharma et al., 2022). In a study on the Kaligandaki basin in Nepal, Pandey and Bardsley (2015) found that vulnerability varied across households due to a combination of social factors and that a ‘poor people first’ approach was needed.

These case studies highlight how demographic, socio-economic, and infrastructure proxies can serve as useful indicators for mapping and comparing social vulnerability to multiple hazards across Nepal.

Nepal’s extensive inequalities drive social vulnerability (Nightingale, 2017). Nepal can only strengthen adaptation and response capacities across all sections of society by addressing the root factors of poverty, inequality, and exclusion (Dixit, 2003).

There is a need to investigate social vulnerability proxies more closely because little is known about their individual validity, uncertainty, and sensitivity. There is also a gap in knowledge on how these indices compare and relate to one another (Gall, 2013).

Integrating intersectional analysis to disaster studies reveals that there is a need for more finer grained analysis which can be provided by a place-based approach.

## 5.7. Social vulnerability – addressing gaps in coverage and conceptual limitations

While existing studies that utilise socio-economic proxies have provided valuable insights into factors shaping social vulnerability, there remain significant gaps in coverage, perspective, and conceptual framing. Here I consider ways to further advance the field of social vulnerability studies in terms of addressing gaps in the sampled literature and extending and deepening theoretical insights. I also consider new approaches that may be developed to conceptualise social vulnerability to multi-hazards. First, the matches and mismatches between the use of concepts and approaches in the literature sample are highlighted to identify current gaps in terms of analysis.

Most sampled studies do not consider social vulnerability as varying across time and space. Thus, in national case studies, social vulnerability is seen implicitly as a homogenous quality that does not vary across regions and communities. I argue instead that what I describe as 'socio-institutional regimes for social vulnerability' exist nationally within which vulnerability attributes and outcomes are emphasised differently, depending on prevailing social and political interests. In turn this suggests there are different scaled narratives and practices of social vulnerability at work in Nepal. A consequence of this blindness to the scale-variant nature of social vulnerability is that studies focus on coping strategies of individuals and communities with only limited or no consideration for relevant national public policies. For example, Posch et al. (2019) only consider a small case study area of 160 households. They give information on how the values and worldviews of these people influence resilience to natural hazards, but they do not consider how resilience and vulnerability outcomes may be influenced by other variables at the district or national scale. Aksha et al. (2019) do consider how vulnerability varies across broad regions of Nepal that has potential to assist emergency managers and policy makers to target specific geographic zones. However, they do not explore the capacities or experiences of communities or people in these zones, which limits the effectiveness of measures they develop. Space is therefore an important though neglected variable in conceptualising and assessing social vulnerability.

The importance of time is also underestimated in most studies. It is often not considered in assessments (Aksha et al., 2020; Samir, 2013), and the great majority of studies provide a ‘snapshot’ rather than having a longitudinal approach to social vulnerability, describing how it changes or whether and how social groups are affected by specific events, such as recent landslides or floods. Exceptions include Sugden et al. 2014 who study the effects of embedded social structures on gendered climate vulnerabilities in south central Nepal, and Guillard-Gonçalves and Zêzere (2018) who describe the predisposition of people during a specific landslide event, indicating that decision pathways before a hazard event must be considered when assessing vulnerability. Dilshad et al. (2019) also mention historical states of vulnerability. However, most work in the sample failed to take account of people or community past experiences of/exposure to multi-hazards, and how this conditions their response. The dynamic nature of societies and how they change with time, for example, in terms of demographic change and population density is also missing from most studies. Yet clearly coping strategies towards multi-hazards will change through, for example, people’s learning, exchange of best practice, and new possibilities for adaptation and mitigation arising as a result of new emergency infrastructure such as early warning and communications systems, migration into and out of hazard-prone landscapes, and provision of greater disaster management resources.

However arguably the most significant gap in the literature is lack of consideration of the iterative relations between physiographic and climatological drivers of multi-hazards and the social capabilities of a place (Raju et al., 2022). This is despite some studies flagging this interrelation, but not elaborating its consequences. Thus, Aksha et al. (2019) for example define social vulnerability as a relational process in that it is a set of physical processes which conditions the social responses and relations around human exposure, risk, and vulnerability. I argue it follows that some communities and individuals are thus better positioned than others to address the confluence of multi-hazard processes through their adaptation and coping strategies. In turn, this means place-based norms and attitudes likely play a crucial role in social vulnerability outcomes for people and communities by shaping their accessibility to social capitals, social networks, and resources.

This gap in the literature was addressed through my development of a new theoretical approach to conceptualise social vulnerability to multi-hazards, via the 'People and Place' pillar of the framework in Chapter 2. This approach argues that mitigating social vulnerability to multi-hazards should be done using locally appropriate strategies sensitive to wider networks of multi-hazard relations and structures of socio-economic relations (Sugden et al., 2014). This calls for appreciation of social vulnerability as a complex nested set of scale-variant processes and phenomena, with policy and governance, social demographic and popular (community and individual) perception, and experience elements brought together. Therefore, I draw attention to the 'socio-institutional regime' of social vulnerability within multi-hazard-prone regions and countries. This regime encapsulates how actors at each scale mobilise and respond to social vulnerability in different ways as, respectively, discourses/narratives, practices, and community-personal experiences, from international to national to sub-national to the local scale. The idea of a socio-institutional regime for social vulnerability to multi-hazards thus emphasises the need to track different ways of framing, experiencing, and responding to vulnerability across geographic scales. In turn, this requires a research design with a varied suite of analytical techniques and data collection methods. This is of particular importance in Nepal where the governance of disaster risk is shared between the state, non-governmental organisations (NGOs), and communities as a result of recent sweeping policy changes.

The 'People and Place' pillar is held in dialectical tension with the 'Hazards and Environment' pillar of the model that was explored in Chapters 3 and 4. At local scale, the pillars ultimately coalesce to recommend a place-based approach to multi-hazard research. Crucially the physical environment of multi-hazards does not dictate social vulnerability; prevailing social relations and physical spaces of multi-hazards are in an iterative relation with one another. They are both continually changing and as one changes, so too does the other, with consequences for both, and for the places these interrelations play out. Figure 5.2 shows this relationship with the connection between environmental processes and social economic relations that creates place-based vulnerability. In turn, place-based dynamics of multi-hazards change according to community and personal risk, exposure and potential, and actual damage and loss. Thus, the physical impact of a disaster can both increase/decrease future social vulnerability. For example, damage to infrastructure increases vulnerability, yet for some people it is the trigger for new coping strategies that can decrease their vulnerability to similar future events.

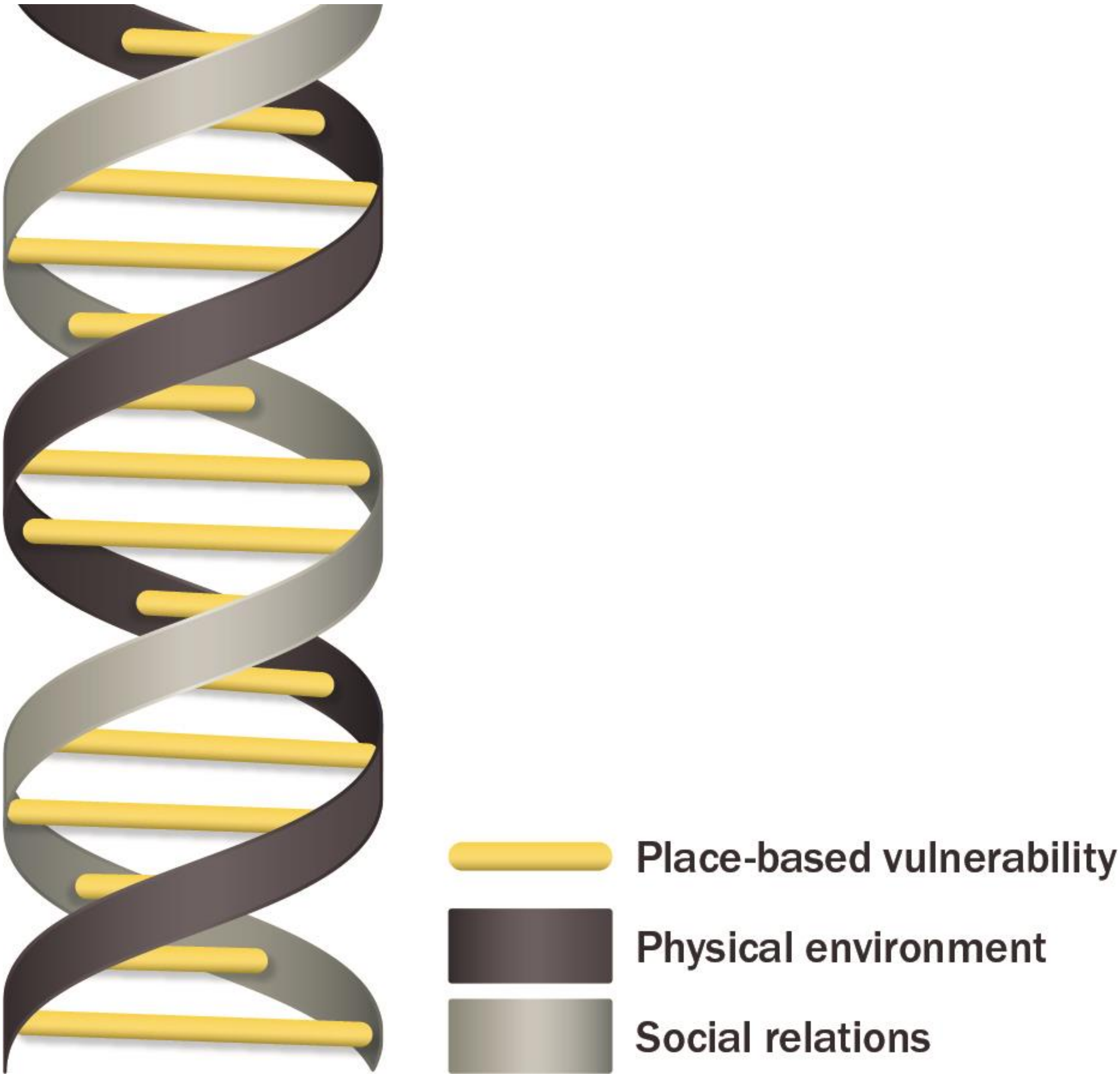


*Figure 5.6. Diagram representing the dialectical tension between physical environment and social-economic relations that explains the dynamic nature of place-based social vulnerability.*

To summarise, I have set out here the state of social vulnerability research in Nepal and have argued more attention must be given to place in multi-hazard research in the country as a conceptual focus for understanding social vulnerability and the methods of multi-hazard assessment and mitigation. This is because place as a concept lends itself well to studying the iterative physical and social basis of multi-hazards that develop in a specific geographical site over space and time. Current debates on social vulnerability tend to get bogged down in the intractability of bringing quantitative and qualitative accounts together. To transcend this impasse, I argue a place-based approach offers new possibilities for research to advance our understanding of multi-hazards in a sustainable development context. How to take this forward is discussed in the next section.

## 5.8. The concept of 'place'

To build the theoretical basis for this approach, the extensive literature on the place concept in human geography is evaluated. This corpus sets out multiple interpretations of this concept, which is conceptualised in different ways. Here I draw attention to three understandings which I argue offer a basis for a place-based approach to evaluating social vulnerability to multi-hazards.

First, place can be understood *as a locality or point in space* that can be defined by co-ordinates on a map (Harvey, 1996). The different objects and features defined by these coordinates and their propinquity (closeness, adjacency) provides a unique sense of geographical identity – a sense of place - and hence a means of distinguishing one place from another.

Secondly, place can be defined not just in physical terms, but *as a moral order that inculcates a sense of place or the identification of place* by encouraging attachment or belonging among people or communities to that place. Here a geographical site helps forge particular social values, attitudes, and behaviours (Agnew, 2011), for example by organising how space is used according to distinct cultural or religious norms such as a site holding special spiritual and/or sacred meanings for certain people or communities. Over time, these norms and beliefs become embedded through historic events and shared memories which define places (Adger et al., 2009).

Thirdly, place can be interpreted as *the action of different networks that 'touch down' in a specific location* to contribute to its historical-geographical development. This includes the interventions of different actors at a variety of scales within these networks – from the actions of individuals to local policy measures, to migrations of whole communities.

Having identified these three conceptualisations of place, each will be discussed in more detail with reference to the work of David Harvey, John Agnew, and Doreen Massey; each has written extensively on place as a concept. These findings will then be related to social vulnerability to multi-hazards and the three conceptualisations will be brought together as a basis of a place-based approach to social vulnerability and multi-hazards.

Harvey (1996: 294) defines place as a location on Earth or as an entity of "permanence" within space and time. He argues that a place with permanence has distinct socio-economic and physical qualities that often lead to it being differentiated from spaces around it, i.e., named or bounded in some way. Thus, places are defined by their connection to other places, and the relation of features, characteristics and/or objects within them. Places become known by these attributes, making them more/less 'favoured' sites in which to live – for example steepness of relief, susceptibility to flooding or drought, resource availability, length of growing season, and altitude. Equally important is their identification as places with particular social conditions which increase/decrease vulnerability – such as social structures, education attainment and skills of residents, and demographic structure. Harvey (1996) argues that over time people have attached less importance to this concept of place because of global technological change and socio-economic development, for example, the invention of the container, aeroplanes, the internet, and mobile phones, that make places more homogenous (Harvey, 1996). Nonetheless, people will choose to voluntarily migrate from a place if they are exposed to continual hazards or stay where they are given strong place attachment that grounds them despite the hazards, leading to the development of different coping strategies. This is the focus for an emerging literature on place attachment (Posch et al., 2019; Swapan and Sadeque, 2021).

Agnew (2011) also discusses conceptualisation of place. For him place is a dimension or grid in which matter is located or a site where geographical attributes and characteristics and their specific adjacencies are contained. This gives rise to place-based qualities and processes which may impact where people choose to live, reside, or work. For example, natural hazards can define the suitability of the place of dwelling, the temporal sequencing in which land is managed, and the desirability of land ownership (Chaudhary et al., 2021). In particular, there is a strong relationship between hazard events and the lives and livelihoods of people living there (Aksha et al., 2019). Social vulnerability to multi-hazards is a function of the social characteristics of people living in a place as much as the physical properties of its landscapes. Agnew (2011) also draws attention to how places are dynamic, allowing the flow of people and information within networks. As a result of this increased flow of people mediated by technological advances, he concurs with Harvey that places are becoming increasingly alike. But he concludes that places are not becoming irrelevant as there will always exist some places where technological change are less, and that evolve differently because of specific social processes and power relations. The evolution of places is thus always causing people to adapt or to leave them (Swapan and Sadeque, 2021). Agnew (2011) describes the theory that places are configured by the intersection of encounters between people, practices, and the socio-economic effects of globalisation. This interplay leads to a chronology of place-based events and actions.

Massey (1991) introduces the concept of place into a wider consideration of time-space compression. Time has brought increased travel, globally imported goods, and the convenience of the internet (amongst other things) which has increased spatial interconnections or flows between places to cause flux and uncertainty in place-based identities. Again, this can lead to a loss of a sense of place and less particularity between places. The injustice and unevenness of time-space compression is also discussed. There will always be some social groups less able to take advantage of these developments, which may be imposed on them by those with mobility and power, to make them marginalised or excluded. People exposed to hazards are often in these disadvantaged groups.

## 5.9. A place-based approach to evaluating social vulnerability

I argue that, as place-based phenomena and processes, multi-hazards and social vulnerability can be brought into engagement with these observations and understandings of place to enrich our understanding through the theoretical framework set out in Chapter 2. This calls for a place-based approach to multi-hazard research which involves consideration of physical processes (e.g., geomorphology and rainfall characteristics) in parallel to social processes (social vulnerability). In Chapters 3 and 4 there was analyses of physical processes related to water-related multi-hazards including their timing, distribution, hydrometeorological drivers, anthropogenic processes, and landscape properties. Crucially these multi-hazard attributes also mediate the social vulnerability of people and places.

Chapter 3 found that water-related multi-hazards are driven by the progression of the South Asian Monsoon which arrives in the west and moves eastwards, affecting the spatial distribution and timing of the hazards across Nepal. This analysis gave a spatial and temporal context to assessing the potential vulnerability to multi-hazards.

From a temporal perspective, the knowledge of seasonal variation of multi-hazards plays an important role in the development of place-based coping strategies. For example, land management practices may change throughout the year to avoid multi-hazard prone areas at particular times. People's beliefs and attitudes may also influence where and at what times of the year they farm, through community institutions such as seasonal calendars (Birkmann, 2006; Twigg et al., 2003). Specific place-based norms of social vulnerability come from community-based learning by locals over long periods about which knowledge and coping strategies are most effective in reducing disaster risk (Rigg et al., 2016). In other cases, beliefs may cause a reluctance to change, and there may even be an attitude of acceptance to the fate of multi-hazards (Posch et al., 2019). The histories within a place - for example, different experiences of exposure to multi-hazards – will result in different attitudes towards them. It may either foster a culture of coping/adapting or a culture of fear/anxiety over such events. People's perception of place may also change making some places more welcoming, opening opportunities for hope and for acting proactively.

The spatial variation of water-related multi-hazards is also important in place-based vulnerability to multi-hazards. For the physical analysis in Chapters 3 and 4, Nepal was divided into nine natural regions based on drainage basin and physiography. It was found in Chapter 3 that most flooding occurred on the fertile land of the Lowlands, and the steep slopes of the Middle Mountains and High Mountains were susceptible to landslides. Social vulnerability is likely to vary spatially in accordance with this exposure, although it is not necessarily areas that have the most exposure to multi-hazards that have the most vulnerable people due to their different situations, adaptations, and mitigation capacities (Gautam, 2017). For example, the High Mountains have less hazards but can be highly vulnerable due to isolation and limited access to health facilities (Aksha et al., 2019). The Middle Mountains of the Gandaki basin have the highest level of co-occurrence of landslides and flooding and may be a very vulnerable area due to a high population density and high urbanisation with major cities such as the capital, Kathmandu. Aksha et al (2019) found that the highest levels of social vulnerability were in the central and western Middle Mountains and the central and eastern Terai despite these areas having similar hydrometeorological and geophysical characteristics. One of the reasons for this was that levels of education and wealth were less in these more vulnerable zones. At a more local scale, a case study by Aksha et al (2020) in the eastern Terai found differences in vulnerability within a city depending on infrastructure. They found that places with a poorer built environment were more vulnerable than those that were rapidly developing. Thus, even within communities different households may have different levels of vulnerability and within those households the vulnerability of individuals also may vary (Samir, 2013).

Furthermore, the proximity to multi-hazards does affect the risk of physical damage and destruction, therefore potentially increasing vulnerability (Giri et al., 2021). There are multiple reasons that people continue to live in such precarity (Rigg et al., 2016). Most clearly, people may be forced to live in a hazardous place because they are unable to afford to live elsewhere or it might be that economic benefits outweigh the risk, as is the case with highly fertile agricultural land alongside rivers susceptible to flooding. People may also remain in a place for traditional reasons i.e., their ancestors lived there, and support networks remain (Chaudhary et al., 2021).

Chapter 4 looked at the environmental processes responsible for variations in hazard occurrence, namely the rainfall signatures driving multi-hazards and the catchment properties that modify the hazard occurrence. This is important for modelling and prediction of water-related multi-hazards that can improve reaction and response. Places within these sub-regions will not only have varied physical catchment properties but also people and communities with disparate connections and variable access to social networks and disaster risk knowledge, for example to government actors or NGOs specialising in disaster risk. In turn, this means fluctuating individual and community adaptive capacity to respond to multi-hazards and to anticipate their occurrence. However, it also opens the possibility of communities working with these state actors in future to shape local policy interventions to respond more effectively to multi-hazard risk.

Consequently, place affects our understanding of multi-hazards and associated social vulnerability. The three conceptualisations draw attention to the ways people can shape their place by responding to environmental conditions while these social relations can rework these conditions to make places distinct from each other. It follows that studies of social vulnerability need to prioritise social networks from small scale, between individuals and families, up to the relations with government actors and disaster risk agencies. This multi-scaled approach is important for realising the spatial variations in social vulnerability to multi-hazards. Time is also an important consideration as both historical and future multi-hazard projections affect vulnerability.

In fostering a place-based approach to multi-hazards, there needs to be respect for people's choices and an understanding of the reasons why people reside in affected places. These understandings and considerations are important for developing strategies that are appropriate for all individuals. The priority must be on informing the actions and the logic of interventions of government actors and aid agencies. This close examination will give a better understanding of vulnerability to multi-hazards.

To achieve this approach, I propose the following research questions and hypotheses as a priority for researchers taking forward a place-based approach to understanding social vulnerability to multi-hazards.

1. What are the drivers of place-based social vulnerability to multi-hazards?

- Multiple factors contribute to the social vulnerability of individuals and communities, including physical, socio-economic, political, ethnic, and demographic variables. As stated in section 5.6, the intersection of these proxies for social vulnerability must be included in a place-based approach.

2. How do external networks of relations shape place-based social vulnerability to multi-hazards?

- The interactions between individuals, communities, and external networks of actors (including state and civil society, including NGOs) help to improve disaster risk resilience of places to multi-hazard events. This is addressed in section 5.8, which discusses the concept of 'place' and how it is related to different networks and the intervention of various actors.

3. What interactions are there between socio-spatial relations and physical places of multi-hazards, and how do they develop over time?

- Social vulnerability is controlled by both physical and climatic characteristics of specific landscapes and the local, socio-economic, political, ethnic, and demographic identities and attributes of individuals and communities living there. Within this chapter there are many linkages to the previous natural science chapters.

The key implications of these research questions and hypotheses for policymakers are a greater sensitivity to the needs of people affected by multi-hazards. Disaster risk reduction strategies nationally must account for the differences in vulnerability between places and the levels of vulnerability of specific communities, taking account of the needs of different social and ethnic groups.

Understanding vulnerability at a fine scale, such as the household or community level, comes with certain practical and economic challenges. Data collection requires significant time, money, and human resources to gather information at a localised level through household level surveys, interviews, FGDs, and observations. Analysis can also be complex and scalability can be an issue. There must be prioritisation of locations and people as well as deciding the sampling approaches required. There will also have to be participation from communities and stakeholders throughout the process to reduce costs, build sustainability, and help overcome barriers related to language, trust, access, and communication.

I propose that national disaster risk reduction strategies must attack both social and physical drivers of vulnerability. There must be attention to national policy, and institutional reform and capacity. In Nepal this is particularly important because governance systems are still evolving and often policy is not implemented effectively.

The place-based approach ultimately gives context into the overlap of physical spaces and social relations. Chapters 3 and 4 investigated the physical processes associated with floods and landslides throughout Nepal concluding that rainfall, landscape characteristics, and human intervention drive and modify the occurrence of water-related multi-hazards. This understanding of the space-time patterns of multi-hazards can be combined with various situational information, such as population density and socio-economic characteristics of the population. The experience of physical hazards and social vulnerability are interconnected although for each area there are particular issues that tie into social vulnerability that are specific to communities.

Consequently, greater research and resources must be employed to evaluate the needs and circumstances for different people and places through time. The place-based approach foregrounds that any assessment of multi-hazard vulnerability is made from the perspective of the vulnerable people themselves. As outlined in the framework in Chapter 2, this knowledge can be used for understanding and co-designing locally appropriate strategies to mitigate social vulnerability.

Policy must evolve to meet the needs of the exposed population and their lived experiences with increasing attention paid to incorporating adaptation in vulnerability analysis. There needs to be an integrative, coupled human-environment approach to the interactions between socio-economic dynamics and how these dynamics shape the resilience of different systems. Capacity building and far-reaching changes in the incentive structure for various disciplines to engage in more policy relevant research which links multi-hazards, vulnerability, and adaptation strategies is also required. The effect of a hazard is amplified or mitigated by particular place-based interconnections like coping strategies as such, community expertise must be brought together with NGOs or the state to reduce disaster risk.

In addition to the framework set out in Chapter 2, there needs to be an expanded vulnerability analysis framework for the assessment of human-environment systems that can be multi-disciplinary in nature and can facilitate the coalescence of models and metrics in a place-based approach.

## 5.10. Conclusions

This chapter elaborates the ‘People and Place’ pillar of the multi-hazard framework set out in Chapter 2 through a narrative review of the social vulnerability literature across Nepal and by describing the benefits of a place-based approach to multi-hazard research. The narrative review identifies the differences, similarities, gaps, and limitations in social vulnerability conceptualisation and analysis. The place-based approach addresses these points by considering how social vulnerability is dynamic and varies across scales and how multi-hazards are specific to places. The research agenda that flows from this must involve a multi-scaled approach bringing together information on policy and governance, social demographic data, and insights into popular perception and experience. It also considers the intertwining of social conditions of people and the physical drivers of multi-hazards. This relates to Chapters 3 and 4 that analyse the patterns and processes surrounding multi-hazards. The coalescence of these projects provides the potential for future work on place-based modelling and prediction of water-related multi-hazards as set out in the framework in Chapter 2. This will have implications on the socio-institutional regime for disaster management.

# Chapter 6 - Conclusions, Synthesis, and Future Work

## 6.1. Introduction

The introduction to the thesis in Chapter 1 provided background to the subject area and a rationale for the research. It outlined the aim which is ***to better understand water-related multi-hazards in a sustainable development context*** and identified four clear research objectives which were addressed in Chapters 2, 3, 4, and 5. These objectives were as follows:

1. To develop a framework for understanding water-related multi-hazards in a sustainable development context. This was the outcome of a bibliometric analysis conducted in Chapter 2.
2. To investigate the patterns of co-occurrence of water-related multi-hazards in Nepal. This was the subject of Chapter 3.
3. To determine the hydrometeorological drivers and river basin controls of water-related multi-hazards. This topic was covered in Chapter 4.
4. To conceptualise social vulnerability to multi-hazards and outline a place-based approach. This was addressed in Chapter 5.

This final chapter concludes the thesis by synthesising the major research findings and recommending areas for future work. This thesis structure is shown in Figure 6.1.

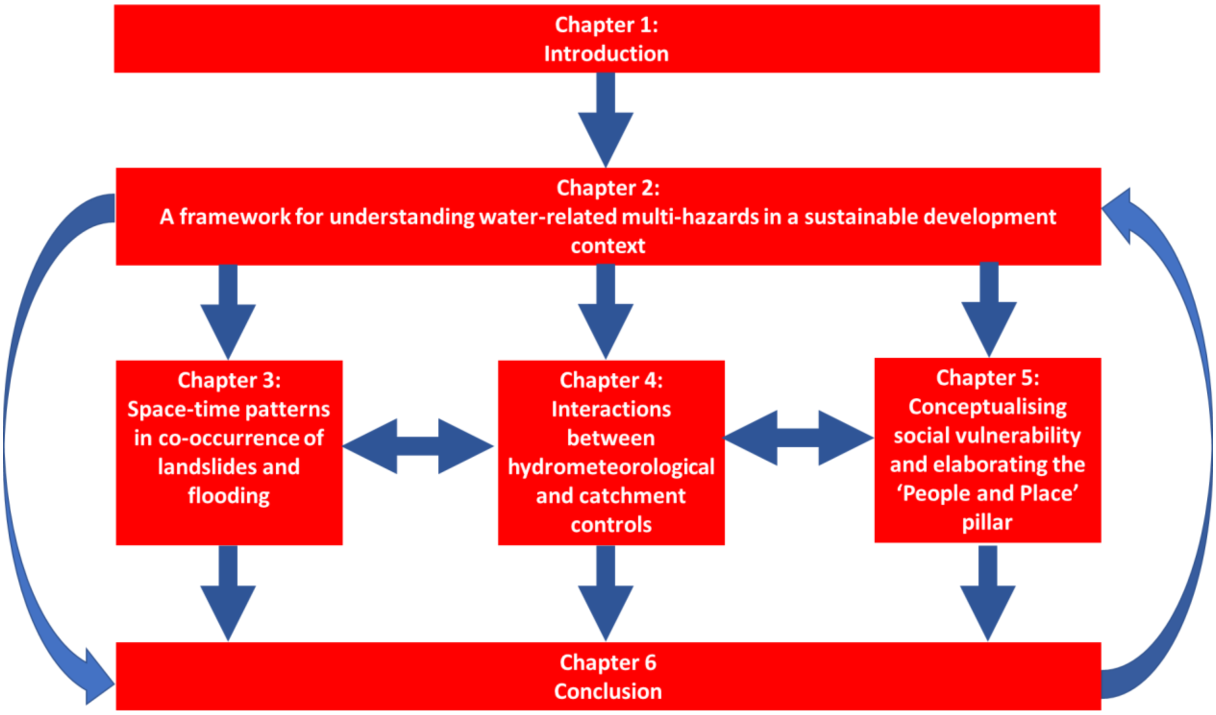


*Figure 6.1. Schematic diagram of the thesis structure. The red boxes show each of the chapter titles and the blue arrows show the interconnections between those chapters.*

## 6.2. Major research contributions

In this thesis, there were a number of major research contributions to methods and new knowledge generation that advance our understanding of water-related multi-hazards in a sustainable development context. These may be summarised as follows (with further explanation in subsections immediately below):

1. The proposal of a novel (and testable) framework which provides a powerful tool for analysing and understanding water-related multi-hazards (Chapter 2).
2. There is space-time variation in the occurrence of water-related multi-hazards in Nepal and there is clear evidence of high co-occurrence across the Middle Mountains and Gandaki river basin (Chapter 3).
3. Water-related multi-hazard occurrence and co-occurrence appears to be driven by rainfall and modified by the basin properties (Chapter 3).
4. Further analysis of these factors found that rainfall is not the only driver of water-related multi-hazards and that there are other contributing factors, including anthropogenic activity, namely road building and land use change (Chapter 4).
5. Evaluation of social vulnerability found that it is shaped by place-based issues, notably coping strategies developed by people living in hazard prone areas who have direct personal experience of their effects (Chapter 5).
6. A place-based approach considers multi-hazards as specific to places, while recognising the intertwining of social relations and physical drivers that comprise these multi-hazards that arise from multiple scales moderating place-based vulnerability (e.g., through public policies, NGO interventions, etc.) (Chapter 5).

### 6.2.1. A framework for understanding water-related multi-hazards in a sustainable development context (Chapter 2)

Chapter 2 developed a novel framework using bibliometric analysis of the multi-hazard literature to identify research gaps and explore the existing approaches to multi-hazard research, thus addressing the first research objective. The outcomes of the bibliometric analysis were that there has been an increase in multi-hazard research over the last 20 years, there is less research in LMICs, and that the terms landslide and flooding commonly co-occur in the literature. It was also found that in the literature there is still a lack of understanding of the interactions, hydrometeorological drivers, and landscape controls on multi-hazards, in addition to an absence of recognition for the social vulnerability of multi-hazard prone places and the people who live there.

The framework provides recommendations on how to understand water-related multi-hazards in a sustainable development context from both a natural and social science perspective. As such, the framework has two pillars, namely ‘Hazards and Environment’ and ‘People and Place’. The ‘Hazards and Environment’ pillar indicates that data should be collected on hazard occurrence, rainfall characteristics, and basin characteristics through hazard inventories, remote sensing, and field observations. It states that this information should be analysed by probability assessments, threshold criteria modelling and GIS hazard mapping to generate knowledge on the drivers of multi-hazards and modifiers of landscape response. The ‘People and Place’ pillar indicates that data should be collected on policy and governance, perception and experience, and social demographic factors through literature/records, community histories, focus groups/interviews, and questionnaires/surveys. This should be analysed by situation analysis, vulnerability assessment, and social vulnerability indexing to generate knowledge on co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards. Combining this knowledge leads the way for a place-based approach to multi-hazard modelling and prediction.

The publication that has come from this work (Docherty et al., 2020) has been recognised and cited in a number of peer reviewed papers. Kreibich et al. (2022) describe the framework as a tool for assessing the two-way interactions and feedbacks between water-related multi-hazards, decision-making processes and conditions of socio-economic systems. Simmonds et al. (2022) and Butte et al. (2022) also cited this work and highlighted the importance of undertaking research to better understand the drivers of multi-hazards particularly in data scarce regions. Zhou et al. (2022) take away from it that it is important to analyse multiple recurrent natural catastrophes holistically. These citations demonstrate the utility of the framework as a tool for understanding multi-hazards.

### 6.2.2. Exploring space-time patterns in co-occurrence of landslides and flooding (Chapter 3)

Following the ‘Hazards and Environment’ element of the framework in Chapter 2, this part of the research investigated the patterns of occurrence and co-occurrence of landslides and flooding in relation to the magnitude and timing of precipitation and the river basin properties that control water-related multi-hazards in Nepal. It was found that there is space-time variation in the occurrence of water-related multi-hazards in Nepal and there is evidence of high co-occurrence in the Middle Mountains and Gandaki river basin. It was also discovered that water-related multi-hazards are influenced by the characteristics of the South Asian Monsoon, notably the monsoon’s pathway across Nepal. In addition, the river basin properties modify both the rainfall patterns and the occurrence and co-occurrence of multi-hazards.

In the analysis, Nepal was divided into nine zones according to the three river basins (Karnali, Gandaki, and Koshi) and three physiographic regions (Lowlands, Middle Mountains, and High Mountains). This was a useful frame to organise the large-scale national assessment of multi-hazards. First, the occurrence and co-occurrence of landslides and flooding during the monsoon was explored. The data was obtained from the DesInventar hazard inventory and analysed to show the space-time distribution of water-related multi-hazards in the nine zones. It was found that there is a high number of floods in the south which decreases on moving north and that the number of landslides is highest in the Middle Mountains and lowest in the Lowlands. The number and timing of hazards varies from east to west with more hazards in the west and peaks in July rather than August. There is co-occurrence of landslides and flooding in all of the zones, but levels of co-occurrence are high across the Middle Mountains and central Gandaki river basin according to a co-occurrence metric that was developed in the chapter.

Using rainfall data derived from remote sensing, the space-time precipitation regimes for the nine zones were also analysed. The movement of the South Asian Monsoon from east to west was evident in the space-time variation over the nine zones. This indicates that precipitation could be a key driver of water-related multi-hazards but there may be other contributing factors modifying the hazard occurrence and co-occurrence.

The basin properties (slope, river density, river gradient, land cover, and geology) were investigated and found to modify both the rainfall and the hazard occurrence and co-occurrence. Rainfall appeared to be modified by the elevation and slope of the Middle Mountains creating an orographic barrier to rainfall and the steep valleys causing localised weather anomalies effecting the occurrence and co-occurrence of multi-hazards. The basin metrics have an effect on landslides because steep slopes are more susceptible and the rate of rainfall infiltration effects slope instability by changing the pore water pressure and weight of the sediment load. These characteristics of the landscape also effect the number of floods by impacting the rate of runoff and other catchment storage and release processes.

The research reveals that both the co-occurrence and the relative drivers vary across the nine zones. Therefore, rainfall and basin properties are paramount in driving and controlling multi-hazards, however there must be other contributing factors. These were investigated in the subsequent chapter (Chapter 4).

### 6.2.3. Understanding space-time interactions between hydrometeorological and catchment controls on water-related multi-hazards (Chapter 4)

Hydrometeorological drivers and river basin controls were analysed in more detail in Chapter 4. The main conclusion was that there is no clear evidence that one particular factor, such as rainfall metrics, Southern Oscillation Index (SOI), or road density, are driving the hazards in isolation; therefore, it appears that it is a combination of hydrometeorological factors and catchment controls that vary in space and time.

Building on the work conducted in Chapters 2 and 3, the ‘Hazards and Environment’ pillar was followed again by analysing rainfall signatures and other factors. Heatmaps were created to compare landslide and flood occurrence to rainfall magnitude, rainfall frequency, rainfall duration, and antecedent rainfall. The heatmaps showed that often floods occur later in the year than landslides indicating that antecedence could be more important in the occurrence of flooding and that years when landslides are high are often followed by subsequent years when the landslides are low which could show evidence of path dependency for landslides.

It was also found that years when flood numbers were high, landslide numbers were also high and vice versa. The five years when hazard occurrence was highest and the five years when hazard occurrence was lowest were chosen for daily rainfall time series analysis. This showed that the rainfall metrics do not follow the same trend annually or spatially and that years when the multi-hazards are high are not associated with years with high rainfall metrics in most cases.

In addition, the SOI was plotted to see if there was any connection between the positive/negative values and multi-hazard occurrence and found that positive SOI values did not tend to correspond to years of high hazard occurrence or rainfall metrics. Road density was also investigated to see if there was any link between the nine zones. The outcome was that the zone with the highest hazard occurrence also had the highest road density indicating that this may be an important factor in driving multi-hazards, however this was done at a very broad scale and further work must look into this at a finer resolution.

The knowledge generated from the ‘Hazards and Environment’ pillar in Chapters 3 and 4 must be combined with an understanding of social vulnerability from the ‘People and Place’ pillar in order to develop a place-based approach to multi-hazard research.

### 6.2.4. Social vulnerability to multi-hazards: Elaborating the 'People and Place' pillar (Chapter 5)

This chapter focused on the 'People and Place' pillar of the multi-hazard framework set out in Chapter 2. This pillar relates social vulnerability to the interaction between people and the physical aspects of multi-hazards. Conceptualising the 'People and Place' pillar, this chapter provided a rationale for a place-based approach by describing different conceptions of place in the Human Geography literature and developing a potential agenda for taking forward social vulnerability studies which goes beyond the snapshot metrics which currently dominate the field.

First, a narrative review of the social vulnerability literature across Nepal was conducted. This review discussed the definitions and concepts of social vulnerability and the analytic approaches used in its quantification. It was found that vulnerability is dynamic and includes multiple factors and dimensions. The concept can be widened to include risk, exposure, susceptibility, sensitivity, and adaptive capacity. It was also found that social vulnerability encompasses physical, social, environmental, and institutional components. In terms of analytical approaches social vulnerability indexing is the dominant form of assessing vulnerability.

Next, there is an analysis of proxies for social vulnerability incorporating empirical evidence from the most recent census on population density, literacy rate, and proportion of men living abroad. This gives a new perspective on how different characteristics intersect to make certain regions, communities, and individuals more or less vulnerable to hazards. It was found that overall population density, literacy rate, and proportion of males living abroad were highest in the Lowlands. The intersection of these proxies and the high risk of flooding creates high vulnerability in the lowlands versus the Middle Mountains and High Mountains. However, there are many different axes of vulnerability to explore such as caste, ethnicity, and gender.

Social vulnerability is a new field of study; therefore, there are many gaps and limitations which are addressed in this thesis. Those discovered were that the approaches to assessing social vulnerability fail to capture the variations across time and space and they underrepresent the iterative-dialectical tension between social and physical processes. The place-based approach addresses these limitations by considering how social vulnerability varies across different scales and addresses how multi-hazards are specific to places.

The concept of place can be understood in three ways. Place can be understood as (1) a point in space, (2) a location with moral order, and (3) a location where different networks are related. The place-based approach considers the social conditions of people in those places, and how these relate to the physical drivers of multi-hazards as these physical and social processes are intertwined.

It was found that lived practices and experiences of people and communities make them more/less vulnerable to multi-hazards. The benefits of a place-based approach are that it considers different coping strategies, social networks, and physical resources used to respond to multi-hazards.

The place-based approach brings together information on policy and governance, social demographic data, and insights into popular perception and experience. This involves a nested research design that includes a varied suite of analytical techniques and data collection methods employed from the small scale, working with individuals and communities, up to district and national scale by working with state actors and disaster risk agencies. The approach prioritises key areas, including information regarding the drivers of social vulnerability, an understanding of the external networks that shape social vulnerability and knowledge of the interaction between social and physical processes.

## 6.3. Synthesis of research

The framework presented in Chapter 2 provided the foundation of the thesis (Fig. 6.2). Chapters 3 and 4 performed analysis according to the ‘Hazards and Environment’ pillar and Chapter 5 conceptualised the ‘People and Place’ pillar in a narrative review. Based on the research in this thesis, there are a number of key considerations to be added to the original framework to improve and further develop it into a more refined and valuable version (Fig. 6.3).

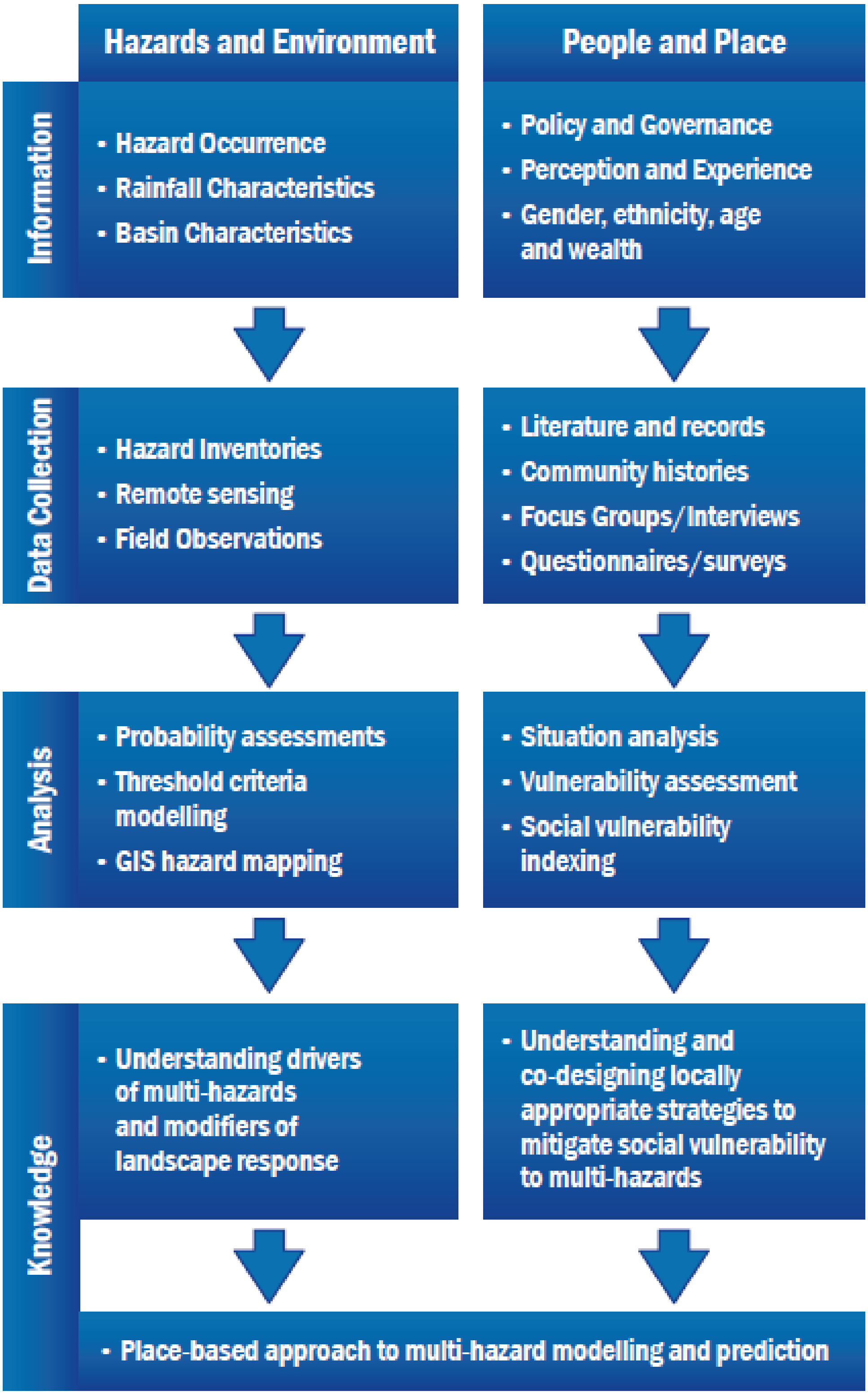


*Figure 6.2. The original framework for understanding water-related multi-hazards in a sustainable development context as presented in Chapter 2. The bullet points show respectively the information required, methods of data collection, methods of analysis, and the knowledge generated that lead to a place-based approach to multi-hazard modelling and prediction.*

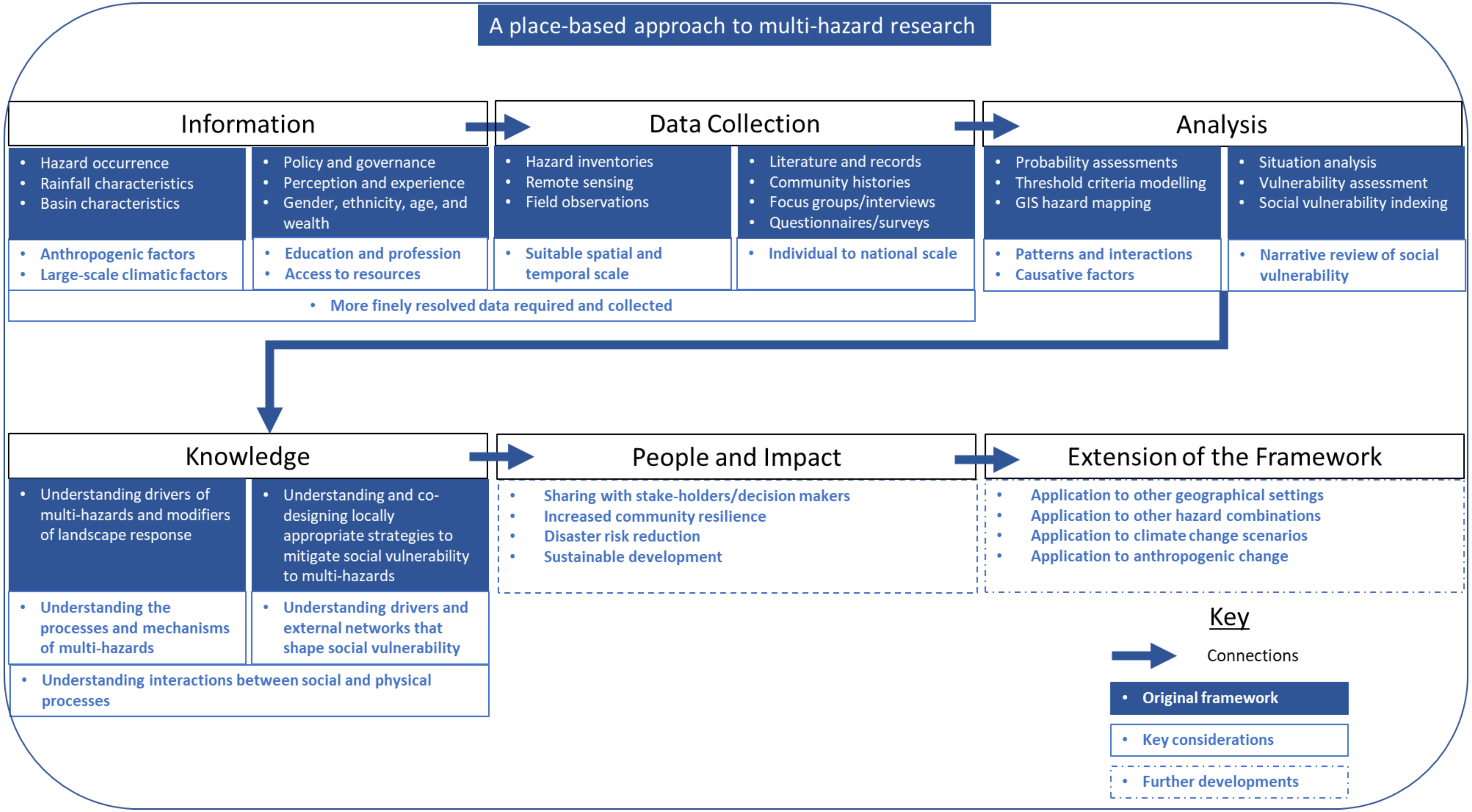


*Figure 6.3. Refined framework for understanding water-related multi-hazards in a sustainable development context which synthesises the research. The blue boxes with white writing indicate content from the original framework, the white boxes with blue writing indicate additional key considerations, and the dotted white boxes with blue writing indicate the potential for further developments in both the people and impact and the extension of the framework sections.*

In the original framework, the pillars ‘Hazards and Environment’ and ‘People and Place’ run parallel coalescing to give a place-based approach to multi-hazard modelling and prediction (Fig. 6.2). In the more refined version, a place-based approach encompasses all of the stages (Fig. 6.3). Conducting the research at all levels is place-based and does not necessarily lead to multi-hazard modelling and prediction but instead a more refined knowledge and understanding.

The pillars ‘Hazards and Environment’ and ‘People and Place’ have not been included in the refined version indicating instead that the stages are concurrent. The sections ‘Information’, ‘Data Collection’, ‘Analysis, and ‘Knowledge’ run horizontal, flowing into one another, and there are additional key considerations at each stage.

It was recognised that more finely resolved data was required at the ‘Information’ and ‘Data Collection’ stage on hazard occurrence, rainfall characteristics, basin characteristics, policy and governance, people’s perception and experience, and gender, ethnicity, age, and wealth. In Chapter 4, I also looked at road building and large-scale climatic factors. These should be considered in the refined framework and also include land use change as part of anthropogenic factors. There were also some additional factors that could be considered in the ‘Information’ section, including people’s education and profession and access to resources. Alternative and additional data sources will be described further in section 6.4, recommendations for future work.

In terms of the ‘Data Collection’ section, a suitable spatial and temporal scale should be chosen for the hazard and environmental data. In our analysis we looked at a broad scale which was an ideal method for looking at the distribution of multi-hazards, precipitation, and basin properties over the whole of Nepal, but this could be refined by looking in more granular detail by using remote sensing or fieldwork. It is also important to collect data from the individual to national scale on the characteristics of people and places.

In the 'Analysis' section of the original framework, there was a focus on modelling and prediction which was beyond the scope of this thesis. These will be discussed further in section 6.4, recommendations for future work. Instead, Chapters 3 and 4 looked at the patterns and interactions of water-related multi-hazards with various causative factors which are vital key considerations for a place-based approach to multi-hazard research.

Analysing data on people and place was done via a narrative review of the social vulnerability literature, an investigation of the spatial variation of vulnerability in Nepal using empirical data in relation to proxies, and an evaluation of place. Restrictions to travel due to the COVID-19 pandemic in 2020 and 2021 meant there was no option of conducting data collection or analyses through fieldwork. Situation analysis, social vulnerability assessment and social vulnerability indexing were not performed as stated in the original framework. These methods must be included in future work however the narrative review in Chapter 5 provided an important understanding that was required for this thesis.

In addition to the knowledge generated on drivers and modifiers of multi-hazards, knowledge of the processes and mechanisms of multi-hazards must also be considered. Drivers and external networks that shape social vulnerability must also be understood in addition to understanding and co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards. The most important key consideration in developing our knowledge and understanding is recognising the interactions between social and physical processes. Sharing this knowledge with stakeholders/decision makers would increase community resilience, reduce disaster risk, and promote sustainable development.

An extension to the framework or further development is that it can be applied to a range of geographical settings, other hazard combinations, climate change scenarios, and other anthropogenic changes. These will be discussed in the next section on recommendations for future work.

## 6.4. Recommendations for future work

Based on the findings of this thesis, recommendations for future work have been highlighted and structured around the key themes set out below: alternative and additional data sources, process understanding, modelling and prediction, people and impact, and extension of the framework.

### 6.4.1. Alternative and additional data sources

Data quality, availability, and accessibility play major roles in improving our understanding of multi-hazards. There is a data shortage on water-related multi-hazards in remote mountainous regions of lower- and middle- income countries (LMICs), particularly in Nepal. In order to implement the proposed framework a large amount of detailed data was required that was not always available. For this reason, there are limitations to the study and alternative methods of data collection should be considered in future work.

Combining our study with complementary data to create a more powerful resource would have improved the study considerably. These would have included:

- Additional or alternative hazard inventories, for example Emergency Events Database (EM-DAT), the Global Landslide Fatality Database (GLFD) and the Dartmouth Flood Observatory (DFO).
- Ground-based rainfall measurements from rain gauges and weather stations.
- Low-cost sensor technology.
- Annual road and land cover data.

- Social vulnerability data from interviews/focus group discussions, and participant observations by conducting fieldwork.
- Secondary data sources within communities which would include community histories and personal testimonies of direct experience of disaster risk events.

The DesInventar hazard database was used to investigate hazard occurrence in Nepal. It is a world leading resource that contains data on over 7000 hazards in Nepal between 1971 and 2013 with 31 variables. The time resolution of this data is limited as it does not extend to present day. However, the DesInventar database was suitable for examining broad scale patterns of multi-hazard occurrence.

An alternative data source that could have been used is the Emergency Events Database (EM-DAT). This database provides comprehensive coverage of natural disasters in Nepal from 1900 until present. It is not as reliable as DesInventar because it relies on media sources rather than government records but it could be used to analyse more recent hazard occurrence in future work.

Another resource is the Global Landslide Fatality Database (GLFD). Formed from media sources and government and aid agency reports, this database extends from 2004 until present day in Nepal but only provides information on landslides and not flooding. Future work could involve combining this resource with flood databases to analyse occurrence of multi-hazards.

Dartmouth flood observatory (DFO) data could have been used to combine data on flooding with the DesInventar database. The flood observatory, now based at the University of Colorado, has created the Global Active Archive of Large Flood Events from 1985 to present obtained from news reports, governmental and international relief agency web sites, and other electronic data sources for reports on major flooding. However, this is incomplete for Nepal and may not record all floods due to a different definition of major flooding. The DFO also use space-based measurement, mapping, and modelling of surface water for flood identification. However, this resource has not been used extensively in Nepal because of false positives due to terrain shadowing (Nigro et al., 2014). Automated approaches to hazard mapping or inventory creation using remote sensed data could also be used to look at smaller regions at a higher spatial resolution in future work.

The use and application of earth observations from satellites in disaster risk management is an exciting area of growth. The rainfall data used in this thesis was derived from the ERA5 gridded precipitation climate dataset and was open and freely available. This covered the time period from 1979 to present and was at a cell size resolution of 30 km. This was the best resource for measuring precipitation regimes and characteristics in Nepal. During the project, work was in progress to develop a new rainfall data set that blends the ERA5 data set with other satellite rainfall products and combine this with rain gauge network data. Integrated approaches like these, using rain gauges, and weather station data, could be used in future work to give higher resolution over mountainous environments and account for the difficulties associated with rain cloud shadowing where satellite data sometimes fails to record when it is cloudy or raining. However, groundbased observations in the Himalayas are limited because they are largely in the lower parts of the catchments due to the difficulties accessing certain regions. This is likely to result in a serious underrepresentation of rainfall.

Combining these official/statutory monitoring networks and remote sensing with citizen science approaches, for instance, working with communities to monitor rainfall and river flow using sensor technologies, rain gauges or smartphone imagery has potential for use as a future data source (Paul et al., 2018). The advantage of citizen science approaches is that it encourages community engagement and empowers people affected by hazards to make their own decisions on adaptation strategies and relocation. The disadvantages of using citizen science methods are that it can cause bias in data collection and sometimes fails to attract community engagement (Cieslik et al., 2019).

Road network data was obtained from open street map (Geofabrik, 2023). This aspect of the project could be prioritised by having road data over successive years to find out how road construction through time has affected the hazard occurrence in the different zones. Investigating proximity of landslides and flooding to new roads would also be an area of future work which would clarify our understanding of the combined effects of rainfall and road building. This could be done through fieldwork or remote sensing. The land cover analysis was also limited by using one map taken from 2022. Thus, future work could look into changes in informal road construction and land cover over a suitable spatial and temporal scale.

Primary data on social vulnerability through interviews and observations would be useful to have had but was unable to be obtained due to restrictions on travel for fieldwork during the COVID-19 pandemic in 2020 and 2021. Future work would include the collection of primary data on responses to multi-hazards to make direct connections between physical multi-hazards and coping strategies. Ideally these would be combined with secondary data sources from within communities including community histories and personal testimonies of direct experience of disaster risk events. This thesis used the most recent census to analyse the differences in social vulnerability between the nine zones. Further work could focus on the social vulnerability within zones using district level data on some proxy metrics and add to the understanding of how different groups are affected by multi-hazards. This would enhance the proposal of a place-based approach.

In summary, future work requires finer resolution analysis with fieldwork and remote sensing to develop a more powerful data resource. This would give the space-time resolution required to drive multi-hazard research forward.

### 6.4.2. Process understanding

Understanding water-related multi-hazards requires progression in thinking on the phenomenon and its variability. This thesis has looked at large-scale water-related multi-hazard patterns and causative factors between regions. Future work must look more directly at analysing the underlying processes and interconnections at different scales and particularly the interconnections between physical, hydrological, and social processes.

This could involve taking more of a nested approach using the nine natural regions to structure the analysis and identify areas or zones in which it would be advisable to conduct more granular research. This could be done through case studies within those zones that would give more information on the processes that are representative of the wider area. These case studies would generate knowledge on the causes, evolution, and impacts of landslides and floods, as well as realizing the critical weather conditions responsible for those particular hydrogeomorphic processes. Their evolution could focus on the sequence of events, whether they are cascading or compound processes.

### 6.4.3. Modelling and prediction

Monitoring and modelling are key components in the generation of forecasts which could provide valuable information on preparing, preventing, and mitigating the impacts of multi-hazards. Future work could use the refined framework to predict the likelihood or probability of slope failures and floods.

This research has provided a knowledge framework to assist in the development of these models and forecasts. Understanding of the occurrence and co-occurrence of hazards and social vulnerabilities makes it possible to consider all the risks present in specific areas. Future work can use statistical or physically based models, such as hazard mapping, early warning systems, probability assessments, sensitivity analysis, and threshold criteria modelling (Barrantes, 2018). Using this knowledge of contexts and regional outcomes, the framework could also be used to look at data sparse regions through simulations or to make projections into the future for scenarios of climate and anthropogenic change.

Climate is changing and the future will see more heat waves, intense storms, heavy precipitation events, and extension of drought areas (Güneralp and Liu, 2015). The refined framework could be used in future work to collect data on, for example, changing levels of precipitation. This would be very valuable in the case of Nepal because it has been found that annual extreme precipitation has increased across Nepal since the end of the 20$^{th}$ century increasing the threat of water-related multi-hazards (Karki et al., 2017; Panthi et al., 2015; Pokharel et al., 2020). Other parts of the world are also experiencing increasing threat of multi-hazards due to climate change which could be analysed using the framework (IPCC, 2021).

In future work the refined framework could also be used as a tool to look at anthropogenic change such as changing land and water management practices. These models would include changes such as the excavation into hillslopes for road building and construction, removal of vegetation/deforestation, and the concentration or redirection of water to unsuitable places (Pradhan et al., 2022).

### 6.4.4. People and Impact

There needs to be a strong understanding of social vulnerability which is often the most complicated element of evaluating hazards. In particular this exposure and vulnerability must be understood in local contexts. The desk-based review and proxy analysis conducted in this thesis was important to understand the key processes, but some more empirical evaluation of social vulnerability must be conducted in the future to assess social vulnerability in Nepal. This would include situation analysis, social vulnerability assessment, and social vulnerability indexing.

Future work could involve the development of detailed case studies exploring how households and communities living with ongoing risk from water-related multi-hazards could benefit from the data generated. This would require focusing on the questions, concerns, and needs of individuals which could supply communities and organisations with support needed where land use planning and relocation are concerned.

There could also be closer attention to indigenous knowledges and coping strategies within place that could be used as a basis for co-producing structures that tackle social vulnerability. A place-based approach enables a more nuanced understanding of multi-hazard research by focusing on a specific place and engaging with communities in those places to better understand how they appreciate multi-hazards and how they make them part of their daily routines by hazard avoidance or risk reduction. This is critical because often communities are not able to direct and inform policy makers even though they have a much better understanding of these hazards and their spatial occurrence.

An important part of future work could be to develop better connections with policy makers, NGOs, and communities about addressing multi-hazards and communicating the research. There remains a gap between international and national policy and what happens locally which must be recognised in future work. There must also be recognition for changing patterns of state and sub-state enforcement and changes in the government.

An enhanced understanding of a place-based approach to multi-hazards brings together local level understandings of hazards and of coping capacities. There is great potential for future work when combined with a more refined understanding of where hydrological processes meet multi-hazards.

### 6.4.5. Extension of the framework

The revised framework shown in Figure 6.3 offers a nuanced understanding of the occurrence of hazards, their drivers and tipping points. This provides a targeted view on water-related multi-hazards in time and space which has great potential for application to other geographical contexts.

It could be used in future work to include other multi-hazard combinations, for example earthquakes and landslides. This would require the collection of different hazard data and analyses by different methods. In the case of earthquake-induced landslides information would be required on the earthquake ground and fault movement and landslide inventories in the aftermath of the earthquake (Sneddon, 2019). It could also be used in other geographical settings such as coastal and volcanic environments.

The versatile framework is designed for use in LMICs but is not restricted by this. It could be applied in countries of various levels of development, such as for storms and hurricanes in the USA, providing they account for the place-based attributes and socio-cultural contexts of different places. As such, it could be used worldwide to further our understanding of multi-hazards. This would not only reduce disaster risk in those places but also further our understanding of the interactions between hazards globally.

## 6.5. Final remarks

This thesis has improved our understanding of water related multi-hazards. It has shown that there is a combination of factors that lead to the occurrence and co-occurrence of multi-hazards and that a place-based approach which considers social vulnerability is vital.

My research highlights the importance of interdisciplinary research and provides a framework for future research in a range of different multi-hazard contexts and settings world-wide. An in-depth grounded understanding of water-related multi-hazards and the communication of this knowledge to stakeholders is essential for any policy and community engagement, which can reduce disaster risks and has potential to save lives and livelihoods.

# References

Abdulwahid, W. M., & Pradhan, B. (2017). Landslide vulnerability and risk assessment for multi-hazard scenarios using airborne laser scanning data (LiDAR). *Landslides*, *14*(3), 1057–1076. https://doi.org/10.1007/s10346-016-0744-0

Adger, W. N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D. R., Otto, L., Johanna, N., & Anita, W. (2009). *Are there social limits to adaptation to climate change ?* 335–354. https://doi.org/10.1007/s10584-008-9520-z

Adhakari, B. R. (2013). Flooding and Inundation in Nepal Terai: Issues and Concerns. *Hydro Nepal: Journal of Water, Energy and Environment*, *12*, 59–65. https://doi.org/10.3126/hn.v12i0.9034

Adhikari, P., Hong, Y., Douglas, K. R., Bach Kirschbaum, D., Gourley, J., Adler, R., Robert Brakenridge, G., Adhikari Á Hong, P. Y., R Douglas, Á. K., Kirschbaum Á R Adler, D. B., & Gourley, J. (2010). *A digitized global flood inventory (1998-2008): compilation and preliminary results*. *55*, 405–422. https://doi.org/10.1007/s11069-010-9537-2

Adhikari, S., & Adhikary, D. K. (2019). *An account of Nepal disasters and economic fallout, Project Research and Management Associates, HAL-01995386*. https://hal.archives-ouvertes.fr/hal-01995386

ADPC, NGI, CECI, & GFDRR. (2010). *Asian Disaster Preparedness Center; Norwegian Geotechnical Institute; Centre for International Studies and*

*Cooperation. Nepal Hazard Risk Assessment*. 1–237. https://www.adpc.net/igo/category/ID276/doc/2013-b27Iym-ADPC-NHRA_Report.pdf

Aksha, S. K., Juran, L., & Resler, L. M. (2018). Spatial and temporal analysis of natural hazard mortality in Nepal. *Environmental Hazards*, *17*(2), 163–179. https://doi.org/10.1080/17477891.2017.1398630

Aksha, S. K., Juran, L., Resler, L. M., & Zhang, Y. (2019). An Analysis of Social Vulnerability to Natural Hazards in Nepal Using a Modified Social Vulnerability Index. *International Journal of Disaster Risk Science*, *10*(1), 103–116. https://doi.org/10.1007/s13753-018-0192-7

Aksha, S. K., Resler, L. M., Juran, L., & Carstensen, L. W. (2020). A geospatial analysis of multi-hazard risk in Dharan, Nepal. *Geomatics, Natural Hazards and Risk*, *11*(1), 88–111. https://doi.org/10.1080/19475705.2019.1710580

Al-Haddad, R. E., Duran, K. L., & Ahmed, S. (2022). A lost generation: perpetual education insecurity among the Rohingya. *Race Ethnicity and Education*, *25*(6), 874–900. https://doi.org/10.1080/13613324.2022.2069738

Allen, S. K., Rastner, P., Arora, M., Huggel, C., & Stoffel, M. (2016). Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. *Landslides*, *13*(6), 1479–1491. https://doi.org/10.1007/s10346-015-0584-3

Ávila, A., Justino, F., Wilson, A., Bromwich, D., & Amorim, M. (2016). Recent precipitation trends, flash floods and landslides in southern Brazil. *Environmental Research Letters*, *11*(11). https://doi.org/10.1088/1748-9326/11/11/114029

Barrantes, G. (2018). Multi-hazard model for developing countries. *Natural Hazards*, *92*(2), 1081–1095. https://doi.org/10.1007/s11069-018-3239-6

Bathrellos, G. D., Skilodimou, H. D., Chousianitis, K., Youssef, A. M., & Pradhan, B. (2017). Suitability estimation for urban development using multi-hazard assessment map. *Science of the Total Environment*, *575*, 119–134. https://doi.org/10.1016/j.scitotenv.2016.10.025

Beccari, B. (2016). A comparative analysis of disaster risk, vulnerability and resilience composite indicators. *PLoS Currents*. https://doi.org/10.1371/currents.dis.453df025e34b682e9737f95070f9b970

Berti, M., Martina, M. L. V., Franceschini, S., Pignone, S., Simoni, A., & Pizziolo, M. (2012). Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. *Journal of Geophysical Research: Earth Surface*, *117*(4), 1–20. https://doi.org/10.1029/2012JF002367

Bir Bista, R. (2019). *Index measurement of climate variability and household vulnerability: A case of western Nepal*. 5–12. www.ecologyjournal.in

Birkmann, J. (2006). Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions. In *Measuring vulnerability to natural hazards: Towards disaster resilient societies* (Vol. 1).

Bischiniotis, K., Van Den Hurk, B., Jongman, B., Coughlan De Perez, E., Veldkamp, T., De Moel, H., & Aerts, J. (2018). The influence of antecedent conditions on flood risk in sub-Saharan Africa. *Hazards Earth Syst. Sci*, *18*, 271–285. https://doi.org/10.5194/nhess-18-271-2018

Blaikie, Piers; Cannon, Terry; Davis, Ian; Wisner, B. (1994). *At Risk: Natural hazards, people's vulnerability, and disasters* (Vol. 23).

Bohlinger, P., & Sorteberg, A. (2018). A comprehensive view on trends in extreme precipitation in Nepal and their spatial distribution. *International Journal of Climatology*, *38*(4), 1833–1845. https://doi.org/10.1002/joc.5299

Breinl, K., Turkington, T., & Stowasser, M. (2015). Simulating daily precipitation and temperature: A weather generation framework for assessing hydrometeorological hazards. *Meteorological Applications*, *22*(3), 334–347. https://doi.org/10.1002/met.1459

Butte, G., Solano-Correa, Y. T., Peppa, M. V., Ruíz-Ordóñez, D. M., Maysels, R., Tuqan, N., Polaine, X., Montoya-Pachongo, C., Walsh, C., & Curtis, T. (2022). A Framework for Water Security Data Gathering Strategies. *Water (Switzerland)*, *14*(18). https://doi.org/10.3390/w14182907

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*(October), 1–21. https://doi.org/10.3389/feart.2014.00026

Carpignano, A., Golia, E., Di Mauro, C., Bouchon, S., & Nordvik, J. P. (2009). A methodological approach for the definition of multi-risk maps at regional level: First application. *Journal of Risk Research*, *12*(3–4), 513–534.

https://doi.org/10.1080/13669870903050269

Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2007). Urban seismic risk evaluation: A holistic approach. *Natural Hazards*, *40*(1), 137–172. https://doi.org/10.1007/s11069-006-0008-8

Chalise, D., Kumar, L., & Kristiansen, P. (2019). Land degradation by soil erosion in Nepal: A review. *Soil Systems*, *3*(1), 1–18. https://doi.org/10.3390/soilsystems3010012

Chaudhary, B. R., Acciaioli, G., Erskine, W., & Chaudhary, P. (2021). Responses of the Tharu to climate change-related hazards in the water sector: Indigenous perceptions, vulnerability and adaptations in the western Tarai of Nepal. *Climate and Development*, *13*(9), 816–829. https://doi.org/10.1080/17565529.2021.1889947

Chaudhary, R. P., Uprety, Y., & Rimal, S. K. (2016). Deforestation in Nepal: Causes, Consequences, and Responses. In *Biological and Environmental Hazards, Risks, and Disasters* (Issue October 2017). https://doi.org/10.1016/B978-0-12-394847-2.00020-6

Chen, H. X., Zhang, S., Peng, M., & Zhang, L. (2016). A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows. *Engineering Geology*, *203*, 15–29. https://doi.org/10.1016/j.enggeo.2015.12.009

Chen, J., Huang, G., & Chen, W. (2021). Towards better flood risk management: Assessing flood risk and investigating the potential mechanism based on machine learning models. *Journal of Environmental Management*, *293*(April), 112810. https://doi.org/10.1016/j.jenvman.2021.112810

Chen, L., van Westen, C. J., Hussin, H., Ciurean, R. L., Turkington, T., Chavarro-Rincon, D., & Shrestha, D. P. (2016). Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps. *Geomorphology*, *273*, 150–167. https://doi.org/10.1016/j.geomorph.2016.07.041

Cieslik, K., Shakya, P., Uprety, M., Dewulf, A., Russell, C., Clark, J., Dhital, M. R., & Dhakal, A. (2019). Building Resilience to Chronic Landslide Hazard Through Citizen Science. *Frontiers in Earth Science*, *7*(November), 1–19. https://doi.org/10.3389/feart.2019.00278

Ciurean, R., Gill, J., Reeves, H. J., O'Grady, S., & Aldridge, T. (2018). Review of environmental multi-hazards research and risk assessments. *British Geological Survey*, 86. http://nora.nerc.ac.uk/id/eprint/524399/

Clement, F., & Sugden, F. (2021). Unheard vulnerability discourses from Tarai-Madhesh, Nepal. *Geoforum*, *126*(August), 68–79. https://doi.org/10.1016/j.geoforum.2021.07.016

Cutter, S. L. (1996). Vulnerability to environmental hazards. *Progress in Human Geography*, *20*(4), 529–539. https://doi.org/10.1177/030913259602000407

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, *18*(4), 598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly*, *84*(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

Dahal, R. K. (2012). Rainfall-induced Landslides in Nepal. *International Journal of Erosion Control Engineering*, *5*(1), 1–8. https://doi.org/10.13101/ijece.5.1

Dahal, R. K., & Hasegawa, S. (2008a). Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology*, *100*(3–4), 429–443. https://doi.org/10.1016/j.geomorph.2008.01.014

Dahal, R. K., & Hasegawa, S. (2008b). Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology*, *100*(3–4), 429–443. https://doi.org/10.1016/J.GEOMORPH.2008.01.014

Dahal, R. K., Hasegawa, S., Nonomura, A., Yamanaka, M., Dhakal, S., & Paudyal, P. (2008). Predictive modelling of rainfall-induced landslide hazard in the Lesser Himalaya of Nepal based on weights-of-evidence. *Geomorphology*, *102*(3–4), 496–510. https://doi.org/10.1016/j.geomorph.2008.05.041

Dai, F. C., & Lee, C. F. (2001a). Frequency-volume relation and prediction of rainfall-induced landslides. *Engineering Geology*, *59*(3–4), 253–266. https://doi.org/10.1016/S0013-7952(00)00077-6

Dai, F. C., & Lee, C. F. (2001b). Frequency-volume relation and prediction of rainfall-induced landslides. *Engineering Geology*, *59*(3–4), 253–266. https://doi.org/10.1016/S0013-7952(00)00077-6

Dai, F. C., Lee, C. F., & Ngai, Y. Y. (2002). Landslide risk assessment and management: An overview. *Engineering Geology*, *64*(1), 65–87.

https://doi.org/10.1016/S0013-7952(01)00093-X

Delalay, M., Ziegler, A. D., Shrestha, M. S., & Gopal, V. (2020). Methodology for future flood assessment in terms of economic damage: Development and application for a case study in Nepal. *Journal of Flood Risk Management*, *13*(3), 1–14. https://doi.org/10.1111/jfr3.12623

Depietri, Y., Dahal, K., & McPhearson, T. (2018). Multi-hazard risks in New York City. *Natural Hazards and Earth System Sciences*, *18*(12), 3363–3381. https://doi.org/10.5194/NHESS-18-3363-2018

Devkota, R. P. D. (2013). Flood Vulnerability through the Eyes of Vulnerable People in Mid-Western Terai of Nepal. *Journal of Earth Science & Climatic Change*, *04*(01), 1–7. https://doi.org/10.4172/2157-7617.1000132

Devkota, S., Sudmeier-Rieux, K., Penna, I., Erble, S., Jaboyedoff, M., Andhikari, A., & Khanal, R. (2014). *Community-Based Bio-Engineering for Eco-Safe Roadsides in Nepal*.

Dhital, M. R. (2015). *Geology of the Nepal Himalaya- Regional Perspective of the Classic Collided Orogen*. https://doi.org/10.1007/978-3-319-02496-7

Dhital, M. R., Khanal, N., & Thapa, K. B. (1993). *The role of Extreme Weather Events, Mass Movements, and Land Use Changes in Increasing Ntural Hazards* (p. 123).

Dilshad, T., Mallick, D., Udas, P. B., Goodrich, C. G., Prakash, A., Gorti, G., Bhadwal, S., Anwar, M. Z., Khandekar, N., Hassan, S. M. T., Habib, N., Abbasi, S. S., Syed, M. A., & Rahman, A. (2019). Growing social vulnerability in the river basins: Evidence from the Hindu Kush Himalaya (HKH) Region. *Environmental Development*, *31*(August 2018), 19–33. https://doi.org/10.1016/j.envdev.2018.12.004

Dixit, A. (2003). Floods and vulnerability: Need to rethink flood management. *Natural Hazards*, *28*(1), 155–179. https://doi.org/10.1023/A:1021134218121

Docherty, J. M., Mao, F., Buytaert, W., Clark, J. R. A., & Hannah, D. M. (2020a). A framework for understanding water-related multi-hazards in a sustainable development context. *Progress in Physical Geography*, *44*(2), 267–284. https://doi.org/10.1177/0309133319900926

Docherty, J. M., Mao, F., Buytaert, W., Clark, J. R. A., & Hannah, D. M. (2020b). A framework for understanding water-related multi-hazards in a sustainable development context. *Progress in Physical Geography: Earth and Environment*, *44*(2), 267–284. https://doi.org/10.1177/0309133319900926

Drakes, O., & Tate, E. (2022). Social vulnerability in a multi-hazard context: A systematic review. *Environmental Research Letters*, *17*(3). https://doi.org/10.1088/1748-9326/ac5140

Duncan, J. M. A., & Biggs, E. M. (2012). Assessing the accuracy and applied use of satellite-derived precipitation estimates over Nepal. *Applied Geography*, *34*, 626–638. https://doi.org/10.1016/j.apgeog.2012.04.001

Eck, N. J. Van, & Waltman, L. (2018). *VOSviewer Manual*. *August*.

Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., Salamon, P., Brown, J. D., Hjerdt, N., Donnelly, C., Baugh, C. A.,

& Cloke, H. L. (2016). Continental and global scale flood forecasting systems. *Wiley Interdisciplinary Reviews: Water*, *3*(3), 391–418. https://doi.org/10.1002/wat2.1137

Eshrati, L., Mahmoudzadeh, A., & Taghvaei, M. (2015). Multi hazards risk assessment , a new methodology. *International Journal of Health System and Disaster Management*, *3*(2), 79. https://doi.org/10.4103/2347-9019.151315

ESRI. (2018). *ArcGIS* (10.7).

Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing*, *24*(4), 230–235. https://doi.org/10.1179/2047480615z.000000000329

Froude, M. J., & Petley, D. N. (2018a). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, *18*(8), 2161–2181. https://doi.org/10.5194/nhess-18-2161-2018

Froude, M. J., & Petley, D. N. (2018b). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, *18*(8), 2161–2181. https://doi.org/10.5194/nhess-18-2161-2018

Gain, A. K., Hoque, M. M., & Booij, M. J. (2008). Spatial assessment of risk of river flood in Dhaka City, Bangladesh. *Climate Change and Disaster Impact Reduction*, 47–52.

Gaire, S., Delgado, R. C., & González, P. A. (2015). Disaster risk profile and existing legal framework of Nepal: Floods and landslides. *Risk Management and Healthcare Policy*, *8*, 139–149. https://doi.org/10.2147/RMHP.S90238

Gall, M. (2013). Indices of Social Vulnerability to Natural Hazards: A comparative evaluation. \, *53*(9), 1689–1699.

Galli, M., Ardizzone, F., Cardinali, M., Guzzetti, F., & Reichenbach, P. (2008). Comparing landslide inventory maps. *Geomorphology*, *94*(3–4), 268–289. https://doi.org/10.1016/j.geomorph.2006.09.023

Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., & Marcomini, A. (2016). A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management*, *168*, 123–132. https://doi.org/10.1016/j.jenvman.2015.11.011

Gautam, D. (2017). Assessment of social vulnerability to natural hazards in Nepal. *Natural Hazards and Earth System Sciences*, *17*(12), 2313–2320. https://doi.org/10.5194/nhess-17-2313-2017

Gautam, D. K., & Dulal, K. (2013). Determination of Threshold Runoff for Flood Warning in Nepalese Rivers. In *Journal of Integrated Disaster Risk Management* (Vol. 3, Issue 1). IDRiM Society. https://doi.org/10.5595/idrim.2013.0061

Gautam, Y. (2017). Seasonal Migration and Livelihood Resilience in the Face of Climate Change in Nepal. *Mountain Research and Development*, *37*(4), 436–445. https://doi.org/10.1659/MRD-JOURNAL-D-17-00035.1

Gentle, P., Thwaites, R., Race, D., & Alexander, K. (2014). Differential impacts of climate change on communities in the middle hills region of Nepal. *Natural Hazards*, *74*(2), 815–836. https://doi.org/10.1007/s11069-014-1218-0

Geofabrik. (2023). *Open Street Map Data Extracts*.

Ghosh, A., & Kar, S. K. (2018). Application of analytical hierarchy process (AHP) for flood risk assessment: a case study in Malda district of West Bengal, India. *Natural Hazards*, *94*(1), 349–368. https://doi.org/10.1007/s11069-018-3392-y

Gill, J. C., & Malamud, B. D. (2014). Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics*, *52*(4), 680–722. https://doi.org/10.1002/2013RG000445

Gill, J. C., & Malamud, B. D. (2017). Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. *Earth-Science Reviews*, *166*, 246–269. https://doi.org/10.1016/j.earscirev.2017.01.002

Gilmour, A. D. A., Bonell, M., & Cassells, D. S. (1987). *The Effects of Forestation on Soil Hydraulic Properties in the Middle Hills of Nepal : A Preliminary Assessment the Mohonk Mountain Conference : The Himalaya-Ganges Problem ( Aug ., 1987 ), pp . 239- Published by : International Mountain Society Stable UR*. *7*(3). https://www.jstor.org/stable/3673199

Giri, M., Bista, G., Singh, P. K., & Pandey, R. (2021). Climate change vulnerability assessment of urban informal settlers in Nepal, a least developed country. *Journal of Cleaner Production*, *307*(May), 127213. https://doi.org/10.1016/j.jclepro.2021.127213

Golian, S., Saghafian, B., & Maknoon, R. (2010). Derivation of Probabilistic Thresholds of Spatially Distributed Rainfall for Flood Forecasting. *Water Resources Management*, *24*(13), 3547–3559. https://doi.org/10.1007/s11269-010-9619-7

GoN. (2017a). *Disaster Risk Reduction and Management Act 37*. https://www.dpnet.org.np/resource/14

GoN. (2017b). *Nepal Disaster Report, 2017 'The Road to Sendai.'* http://drrportal.gov.np/uploads/document/1321.pdf

GoN. (2019). *Nepal Disaster Report 2019 1–54*. https://www.preventionweb.net/publications/view/69000

GoN. (2021). *National Population and Housing Censsu 2021*.

GoN. (2023). *Agricultural Census of Nepal 2023*. https://www.agricensusnepal.gov.np/post/10_64fc41ca89e94

Guillard-Gonçalves, C., & Zêzere, J. L. (2018). Combining social vulnerability and physical vulnerability to analyse landslide risk at the municipal scale. *Geosciences (Switzerland)*, *8*(8). https://doi.org/10.3390/geosciences8080294

Güneralp, B., Güneralp, I., & Liu, Y. (2015). Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, *31*, 217–225. https://doi.org/10.1016/j.gloenvcha.2015.01.002

Hagen, T. (1969). *Report on the geological survey of Nepal, Kommissionsverlag von Gebruder Fretz AG*.

Hamm, A., Arndt, A., Kolbe, C., Wang, X., Thies, B., Boyko, O., Reggiani, P., Scherer, D., Bendix, J., & Schneider, C. (2020). Intercomparison of gridded precipitation datasets over a sub-region of the central himalaya and the southwestern tibetan plateau. *Water (Switzerland)*, *12*(11). https://doi.org/10.3390/w12113271

HAN, J., WU, S., & WANG, H. (2007). Preliminary Study on Geological Hazard Chains. *Earth Science Frontiers*, *14*(6), 11–20. https://doi.org/10.1016/s1872-

5791(08)60001-9

Hannah, D. M., Kansakar, S. R., Gerrard, A. J., & Rees, G. (2005). Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *Journal of Hydrology*, *308*(1–4), 18–32. https://doi.org/10.1016/j.jhydrol.2004.10.018

Hannah, D. M., Kansakar, S. R., & Gerrard, J. (2005). Identifying potential hydrological impacts of climatic variability and change for Himalayan basins of Nepal. *IAHS-AISH Publication*, *295*, 120–130.

Harvey. (1996). *From Space to Place and Back Again*.

Haughton, G., & White, I. (2018). Risky spaces: Creating, contesting and communicating lines on environmental hazard maps. *Transactions of the Institute of British Geographers*, *43*(3), 435–448. https://doi.org/10.1111/tran.12227

Hewitt, K., & Burton, I. (1973). American Geographical Society Review Reviewed Work(s): The Hazardousness of a Place: A Regional Ecology of Damaging Events. *Geographical Review*, *63*(1), 134–136. http://www.jstor.org/stable/213252

Hoermann, B., & Kollmair, M. (2009). *Labour Migration and Remittances in the Hindu Kush-Himalayan Region*.

Hovius, N., Stark, C. P., & Allen, P. A. (1997). Sediment flux from a mountain belt derived by landslide mapping. *Geology*, *25*(3), 231–234. https://doi.org/10.1130/0091-7613(1997)025<0231:SFFAMB>2.3.CO;2

Huggel, C., Carey, M., Emmer, A., Frey, H., Walker-Crawford, N., & Wallimann-

Helmer, I. (2020). Anthropogenic climate change and glacier lake outburst flood risk: Local and global drivers and responsibilities for the case of lake Palcacocha, Peru. *Natural Hazards and Earth System Sciences*, *20*(8), 2175–2193. https://doi.org/10.5194/nhess-20-2175-2020

Human Development Report (HDR). (2019). *Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century*.

ICIMOD. (2022). *Land cover of Nepal*. https://rds.icimod.org/Home/DataDetail?metadataId=1972729

IPCC. (2021). Climate Change 2021 The Physical Science Basis WGI. In *Bulletin of the Chinese Academy of Sciences* (Vol. 34, Issue 2).

Iverson, R. M. (2000). Landslide triggering by rain infiltration. *Water Resources Research*, *36*(7), 1897–1910. https://doi.org/10.1029/2000WR900090

Jansky, L., Ives, J. D., Furuyashiki, K., & Watanabe, T. (2002). Global mountain research for sustainable development. *Global Environmental Change*, *12*(3), 231–239. https://doi.org/10.1016/S0959-3780(02)00015-8

John Agnew. (2011). Chapter 23: Space and Place John Agnew (University of California, Los Angeles) in J. Agnew and D. Livingstone (eds.). *Handbook of Geographical Knowledge*, *2011*.

Johnson, K., Depietri, Y., & Breil, M. (2016). Multi-hazard risk assessment of two Hong Kong districts. *International Journal of Disaster Risk Reduction*, *19*, 311–323. https://doi.org/10.1016/j.ijdrr.2016.08.023

Johnson, R. M., Edwards, E., Gardner, J. S., & Diduck, A. P. (2018). Community vulnerability and resilience in disaster risk reduction: an example from Phojal Nalla, Himachal Pradesh, India. *Regional Environmental Change*, *18*(7), 2073–2087. https://doi.org/10.1007/s10113-018-1326-6

Jones, J. N., Boulton, S. J., Stokes, M., Bennett, G. L., & Whitworth, M. R. Z. (2021). 30-year record of Himalaya mass-wasting reveals landscape perturbations by extreme events. *Nature Communications 2021 12:1*, *12*(1), 1–15. https://doi.org/10.1038/s41467-021-26964-8

Jones, L., & Boyd, E. (2011). Exploring social barriers to adaptation: Insights from Western Nepal. *Global Environmental Change*, *21*(4), 1262–1274. https://doi.org/10.1016/j.gloenvcha.2011.06.002

Kanda, N., Negi, H. S., Rishi, M. S., & Kumar, A. (2020). Performance of various gridded temperature and precipitation datasets over northwest himalayan region. *Environmental Research Communications*, *2*(8). https://doi.org/10.1088/2515-7620/ab9991

Kansakar, S. R., Hannah, D. M., Gerrard, J., & Rees, G. (2004). Spatial pattern in the precipitation regime in Nepal. *International Journal of Climatology*, *24*(13), 1645–1659. https://doi.org/10.1002/joc.1098

Kappes, M. S., Keiler, M., von Elverfeldt, K., & Glade, T. (2012). Challenges of analyzing multi-hazard risk: A review. *Natural Hazards*, *64*(2), 1925–1958. https://doi.org/10.1007/s11069-012-0294-2

Kappes, M. S., Papathoma-Köhle, M., & Keiler, M. (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Applied Geography*, *32*(2), 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002

Karki, R., ul Hasson, S., Schickhoff, U., Scholten, T., & Böhner, J. (2017a). Rising precipitation extremes across Nepal. *Climate*, *5*(1), 1–25. https://doi.org/10.3390/cli5010004

Karki, R., ul Hasson, S., Schickhoff, U., Scholten, T., & Böhner, J. (2017b). Rising Precipitation Extremes across Nepal. *Climate 2017, Vol. 5, Page 4*, *5*(1), 4. https://doi.org/10.3390/CLI5010004

Karpouzoglou, T., Dewulf, A., & Clark, J. (2016a). Environmental Science & Policy Advancing adaptive governance of social-ecological systems through theoretical multiplicity. *Environmental Science and Policy*, *57*, 1–9. https://doi.org/10.1016/j.envsci.2015.11.011

Karpouzoglou, T., Dewulf, A., & Clark, J. (2016b). Environmental Science & Policy Advancing adaptive governance of social-ecological systems through theoretical multiplicity. *Environmental Science and Policy*, *57*, 1–9. https://doi.org/10.1016/j.envsci.2015.11.011

Keating, A., Campbell, K., Mechler, R., Mochizuki, J., Liu, W., Szoenyi, M., & Mcquistan, C. (2017). *Disaster resilience : what it is and how it can engender a meaningful change in development policy*. *35*(1), 65–91.

Khaing, Z. M., Zhangid, K., Sawano, H., Bhakra Shrestha, B., Sayama, T., & Nakamura, K. (2019). *Flood hazard mapping and assessment in data-scarce Nyaungdon area, Myanmar*. https://doi.org/10.1371/journal.pone.0224558

Kirschbaum, D., Adler, R., Adler, D., Peters-Lidard, C., Huffman, G., Kirschbaum, D., Adler, R., Adler, D., Peters-Lidard, C., & Huffman, G. (2012). Global Distribution of Extreme Precipitation and High-Impact Landslides in 2010 Relative to

Previous Years. *Journal of Hydrometeorology*, *13*(5), 1536–1551. https://doi.org/10.1175/JHM-D-12-02.1

Kirschbaum, D., Kapnick, S. B., Stanley, T., & Pascale, S. (2020). Changes in Extreme Precipitation and Landslides Over High Mountain Asia. *Geophysical Research Letters*, *47*(4), 1–9. https://doi.org/10.1029/2019GL085347

Kirschbaum, D., Stanley, T., & Zhou, Y. (2015). Spatial and temporal analysis of a global landslide catalog. *Geomorphology*, *249*, 4–15. https://doi.org/10.1016/j.geomorph.2015.03.016

Korswagen, P. A., Jonkman, S. N., & Terwel, K. C. (2019). Probabilistic assessment of structural damage from coupled multi-hazards. *Structural Safety*, *76*(June 2018), 135–148. https://doi.org/10.1016/j.strusafe.2018.08.001

Krakauer, N. Y., Pradhanang, S. M., Lakhankar, T., & Jha, A. K. (2013). Evaluating satellite products for precipitation estimation in mountain regions: A case study for Nepal. *Remote Sensing*, *5*(8), 4107–4123. https://doi.org/10.3390/rs5084107

Kreibich, H., de Ruiter, M. C., Goda, K., Keiler, M., Suppasri, A., & Malamud, B. D. (2022). Critical research in the water-related multi-hazard field. *Nature Sustainability*, *5*(2), 90–91. https://doi.org/10.1038/s41893-021-00833-0

Kucera, P. A., pauL Kucera,  by, ebert,  eLizabeth, Joseph turK, F., Levizzani, vincenzo, Kirschbaum,  daLia, tapiador, F. J., & Loew,  aLexander. (2012). *PRECIPITATION FROM SPACE Advancing Earth System Science*. https://doi.org/10.1175/BAMS-D-11-00171.1

Kumar, A., Hughes, P. N., Toll, D. G., Coningham, R. A. E., Davis, C., Sarhosis, V., Wilkinson, S., Joshi, A., Weise, K., Maskey, P. N., Acharya, K. P., & Kunwar, R. B. (2019). Damage assessment within the Kathmandu valley's World Heritage Monument Zones after 2015 Gorkha Earthquake. *17th European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2019 - Proceedings*, *2019-Septe*. https://doi.org/10.32075/17ECSMGE-2019-1018

Kundzewicz, Z. W., Stoffel, M., Wyzga, B., Ruiz-Villanueva, V., Niedźwiedź, T., Kaczka, R., Ballesteros-Cánovas, J. A., Pińskwar, I., Łupikasza, E., Zawiejska, J., Mikuś, P., Choryński, A., Hajdukiewicz, H., Spyt, B., & Janecka, K. (2017). Changes of flood risk on the northern foothills of the Tatra Mountains. *Acta Geophysica*, *65*(4), 799–807. https://doi.org/10.1007/s11600-017-0075-0

Kuran, C. H. A., Morsut, C., Kruke, B. I., Krüger, M., Segnestam, L., Orru, K., Nævestad, T. O., Airola, M., Keränen, J., Gabel, F., Hansson, S., & Torpan, S. (2020). Vulnerability and vulnerable groups from an intersectionality perspective. *International Journal of Disaster Risk Reduction*, *50*(August). https://doi.org/10.1016/j.ijdrr.2020.101826

Lane, S. N., Brookes, C. J., Kirkby, M. J., & Holden, J. (2004). A network-index-based version of TOPMODEL for use with high-resolution digital topographic data. *Hydrological Processes*, *18*(1), 191–201. https://doi.org/10.1002/hyp.5208

Lewis, J. (1984). A multi???hazard history of Antigua. *Disasters*, *8*(3), 190–197. https://doi.org/10.1111/j.1467-7717.1984.tb00874.x

Liu, K., Wang, M., Cao, Y., Zhu, W., & Yang, G. (2018). Susceptibility of existing and planned Chinese railway system subjected to rainfall-induced multi-hazards. *Transportation Research Part A: Policy and Practice*, *117*(May), 214–226.

https://doi.org/10.1016/j.tra.2018.08.030

Liu, W., Dugar, S., McCallum, I., Thapa, G., See, L., Khadka, P., Budhathoki, N., Brown, S., Mechler, R., Fritz, S., Shakya, P., Liu, W., Dugar, S., McCallum, I., Thapa, G., See, L., Khadka, P., Budhathoki, N., Brown, S., … Shakya, P. (2018). Integrated Participatory and Collaborative Risk Mapping for Enhancing Disaster Resilience. *ISPRS International Journal of Geo-Information*, *7*(2), 68. https://doi.org/10.3390/ijgi7020068

Malamud, B. D., Turcotte, D. L., Guzzetti, F., & Reichenbach, P. (2004). Landslide inventories and their statistical properties. *Earth Surface Processes and Landforms*, *29*(6), 687–711. https://doi.org/10.1002/esp.1064

Mao, F., Clark, J., Buytaert, W., Krause, S., & Hannah, D. M. (2018). Water sensor network applications: Time to move beyond the technical? *Hydrological Processes*, *32*(16), 2612–2615. https://doi.org/10.1002/hyp.13179

Martina, M. L. V., Todini, E., & Libralon, A. (2006). A Bayesian decision approach to rainfall thresholds based flood warning. *Hydrology and Earth System Sciences*, *10*(3), 413–426. https://doi.org/10.5194/hess-10-413-2006

Massey, D. (1991). A global sense of place. *Marxism Today*. http://www.aughty.org/pdf/global_sense_place.pdf

McAdoo, B., Quak, M., Gnyawali, K., Adhikari, B., Devkota, S., Rajbhandari, P., & Sudmeier, K. (2018). Brief communication: Roads and landslides in Nepal: How development affects risk. *Natural Hazards and Earth System Sciences Discussions*, *1979*, 1–6.

Mccallum, I., Liu, W., See, L., Mechler, R., & Keating, A. (2016). Technologies to Support Community Flood Disaster Risk Reduction. *International Journal of Disaster Risk Science*, *7*(2), 198–204. https://doi.org/10.1007/s13753-016-0086-5

Meteorology, D. of H. and. (2015). *Downloads*. https://www.dhm.gov.np/downloads

Miao, Q., Yang, D., Yang, H., & Li, Z. (2016). Establishing a rainfall threshold for flash flood warnings in China's mountainous areas based on a distributed hydrological model. *Journal of Hydrology*, *541*, 371–386. https://doi.org/10.1016/j.jhydrol.2016.04.054

Mignan, A., Komendantova, N., Scolobig, A., & Fleming, K. (2017). Multi-Risk Assessment and Governance. *Handbook of Disaster Risk Reduction and Management*, 357–381. https://doi.org/10.1142/9789813207950_0014

Mignan, A., Wiemer, S., & Giardini, D. (2014). The quantification of low-probability-high-consequences events: Part I. A generic multi-risk approach. *Natural Hazards*, *73*(3), 1999–2022. https://doi.org/10.1007/s11069-014-1178-4

Monsieurs, E., Jacobs, L., Michellier, C., Basimike Tchangaboba, J., Ganza, G. B., Kervyn, F., Maki Mateso, J. C., Mugaruka Bibentyo, T., Kalikone Buzera, C., Nahimana, L., Ndayisenga, A., Nkurunziza, P., Thiery, W., Demoulin, A., Kervyn, M., & Dewitte, O. (2018). Landslide inventory for hazard assessment in a data-poor context: a regional-scale approach in a tropical African environment. *Landslides*, *15*(11), 2195–2209. https://doi.org/10.1007/s10346-018-1008-y

Muñoz-Torrero Manchado, A., Allen, S., Ballesteros-Cánovas, J. A., Dhakal, A., Dhital, M. R., & Stoffel, M. (2021a). Three decades of landslide activity in western Nepal: new insights into trends and climate drivers. *Landslides*, *18*(6), 2001–2015. https://doi.org/10.1007/s10346-021-01632-6

Muñoz-Torrero Manchado, A., Allen, S., Ballesteros-Cánovas, J. A., Dhakal, A., Dhital, M. R., & Stoffel, M. (2021b). Three decades of landslide activity in western Nepal: new insights into trends and climate drivers. *Landslides*, *18*(6), 2001–2015. https://doi.org/10.1007/s10346-021-01632-6

Muñoz-Torrero Manchado, A., Antonio Ballesteros-Cánovas, J., Allen, S., & Stoffel, M. (2022). Deforestation controls landlside susceptibility in Far-Western Nepal. *Catena*, *219*(February). https://doi.org/10.1016/j.catena.2022.106627

Mysiak, J., Torresan, S., Bosello, F., Mistry, M., Amadio, M., Marzi, S., Furlan, E., & Sperotto, A. (2018). Climate risk index for Italy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2121), 20170305. https://doi.org/10.1098/rsta.2017.0305

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., & Jaedicke, C. (2006). Global landslide and avalanche hotspots. *Landslides*, *3*(2), 159–173. https://doi.org/10.1007/s10346-006-0036-1

Nakano, G., Suwa, S., Gautama, A., & Yamori, K. (2020). Long-term evaluation of proactive attitudes toward disaster education in Nepal. *International Journal of Disaster Risk Reduction*, *50*(January), 101866. https://doi.org/10.1016/j.ijdrr.2020.101866

National Centres for Environmental Information. (2022). *El Nino/Southern Oscillation (ENSO)*. https://www.ncei.noaa.gov/access/monitoring/enso/soi

Nayava, J. L., Bhusal, J. K., Paul, J. D., Buytaert, W., Neupane, B., Gyawali, J., & Poudyal, S. (2022). Changing precipitation patterns in far-western Nepal in relation to landslides in Bajhang and Bajura districts. *Geographical Journal of Nepal*, *15*, 23–40. https://doi.org/10.3126/gjn.v15i01.42884

Nied, M., Pardowitz, T., Nissen, K., Ulbrich, U., Hundecha, Y., & Merz, B. (2014). On the relationship between hydro-meteorological patterns and flood types. *Journal of Hydrology*, *519*(PD), 3249–3262. https://doi.org/10.1016/J.JHYDROL.2014.09.089

Nightingale, A. J. (2017). Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, *84*(June 2016), 11–20. https://doi.org/10.1016/j.geoforum.2017.05.011

Nigro, J., Slayback, D., Policelli, F., & Brakenridge, G. R. (2014). NASA/DFO MODIS Near Real-Time (NRT) Global Flood Mapping Product Evaluation of Flood and Permanent Water Detection. *Evaluation, Greenbelt, MD*, 27.

Osipian, A. L. (2016). Disaster Profiteers: How Natural Disasters Make the Rich Richer and the Poor Even Poorer. *Contemporary Sociology: A Journal of Reviews*, *45*(6), 773–774. https://doi.org/10.1177/0094306116671949jj

Oven, K. J. (2009). Landscape, Livelihoods and Risk: Community Vulnerability to Landslides in Nepal. *Doctoral Dissertation, Durham University*.

Overton, a. K. (2009). A guide to the siting, exposure and calibration of automatic weather stations for synoptic and climatological observations. *Exposure*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:A+Guide+to+th

e+Siting+,+Exposure+and+Calibration+of+Automatic+Weather+Stations+for+Synoptic+and+Climatological+Observations#0

Pandey, R., & Bardsley, D. K. (2015). Social-ecological vulnerability to climate change in the Nepali Himalaya. *Applied Geography*, *64*, 74–86. https://doi.org/10.1016/j.apgeog.2015.09.008

Pandey, V. P., Sharma, A., Dhaubanjar, S., Bharati, L., & Joshi, I. R. (2019). Climate shocks and responses in Karnali-Mahakali Basins, Western Nepal. *Climate*, *7*(7). https://doi.org/10.3390/CLI7070092

Pangali Sharma, T. P., Zhang, J., Khanal, N. R., Nepal, P., Pangali Sharma, B. P., Nanzad, L., & Gautam, Y. (2022). Household Vulnerability to Flood Disasters among Tharu Community, Western Nepal. *Sustainability (Switzerland)*, *14*(19). https://doi.org/10.3390/su141912386

Panthi, J., Dahal, P., Shrestha, M. L., Aryal, S., Krakauer, N. Y., Pradhanang, S. M., Lakhankar, T., Jha, A. K., Sharma, M., & Karki, R. (2015). Spatial and temporal variability of rainfall in the Gandaki River Basin of Nepal Himalaya. *Climate*, *3*(1), 210–226. https://doi.org/10.3390/cli3010210

Panwar, V., & Sen, S. (2020). Disaster Damage Records of EM-DAT and DesInventar: A Systematic Comparison. *Economics of Disasters and Climate Change*, *4*(2), 295–317. https://doi.org/10.1007/s41885-019-00052-0

Papathoma-Köhle, M., Kappes, M., Keiler, M., & Glade, T. (2011). Physical vulnerability assessment for alpine hazards: State of the art and future needs. In *Natural Hazards* (Vol. 58, Issue 2, pp. 645–680). https://doi.org/10.1007/s11069-010-9632-4

Paudel, B., Zhang, Y. li, Li, S. cheng, Liu, L. shan, Wu, X., & Khanal, N. R. (2016). Review of studies on land use and land cover change in Nepal. *Journal of Mountain Science*, *13*(4), 643–660. https://doi.org/10.1007/s11629-015-3604-9

Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J. A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D. M., Stoffel, M., Dewulf, A., Dhital, M. R., Liu, W., Nayaval, J. L., Neupane, B., Schiller, A., Smith, P. J., & Supper, R. (2018). Citizen science for hydrological risk reduction and resilience building. *WIREs Water*, *5*(1), 1–15. https://doi.org/10.1002/wat2.1262

Pearson, C. J., Reaney, S. M., Perks, M. T., Hortobagyi, B., Rosser, N. J., & Large, A. R. G. (2022). Identification of floodwater source areas in Nepal using SCIMAP-Flood. *Journal of Flood Risk Management*, *June*, 1–16. https://doi.org/10.1111/jfr3.12840

Pei, B., Pang, W., Testik, F. Y., Ravichandran, N., & Liu, F. (2014). Mapping joint hurricane wind and surge hazards for Charleston, South Carolina. *Natural Hazards*, *74*(2), 375–403. https://doi.org/10.1007/s11069-014-1185-5

Pescaroli, G., & Alexander, D. (2016). Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Natural Hazards*, *82*(1), 175–192. https://doi.org/10.1007/s11069-016-2186-3

Pescaroli, G., & Alexander, D. (2018). *Understanding Compound , Interconnected , Interacting , and Cascading Risks : A Holistic Framework*. *38*(11). https://doi.org/10.1111/risa.13128

Petal. (2006). *C om m uni ty-ba s ed con s tru cti on f o r d i s a s t er ri s k re d ucti o n Ma r l a Pe ta l , R e b e ka h Gr e e n , Il a n K e l m a n , R a j i b Sh a w a nd*

*A m od D i xi t*. *Twigg 2004*.

Petley, D. N. (2010). On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia. *Quarterly Journal of Engineering Geology and Hydrogeology*, *43*(4), 487–496. https://doi.org/10.1144/1470-9236/09-001

Petley, D. N., Hearn, G. J., Hart, A., Rosser, N. J., Dunning, S. A., Oven, K., & Mitchell, W. A. (2007a). Trends in landslide occurrence in Nepal. *Natural Hazards*, *43*(1), 23–44. https://doi.org/10.1007/s11069-006-9100-3

Petley, D. N., Hearn, G. J., Hart, A., Rosser, N. J., Dunning, S. A., Oven, K., & Mitchell, W. A. (2007b). Trends in landslide occurrence in Nepal. *Natural Hazards*, *43*(1), 23–44. https://doi.org/10.1007/s11069-006-9100-3

Pokharel, B., Wang, S. Y. S., Meyer, J., Marahatta, S., Nepal, B., Chikamoto, Y., & Gillies, R. (2020). The east–west division of changing precipitation in Nepal. *International Journal of Climatology*, *40*(7), 3348–3359. https://doi.org/10.1002/joc.6401

Pokhrel, D., Bhandari, B. S., & Viraraghavan, T. (2009). Natural hazards and environmental implications in Nepal. *Disaster Prevention and Management: An International Journal*, *18*(5), 478–489. https://doi.org/10.1108/09653560911003679

Posch, E., Hoferl, K. M., Steiger, R., Bell, R., & Gurung, L. (2019). Ke garne? How Values and Worldviews Influence Resilience to Natural Hazards: A Case Study from Mustang, Nepal. *Mountain Research and Development*, *39*(4), R10–R19. https://doi.org/10.1659/MRD-JOURNAL-D-19-00005.1

Poshan, D., Sharma, J., Marshak, A., & Stites, E. (2013). *Living in the Margins : Coping with Flood Risks and Managing Livelihoods in Nepal ' s Far-western Terai*. 1–42. http://fic.tufts.edu/assets/TUFTS_1385_Nepal_2_online-UPDATED.pdf

Pradhan, S., Toll, D. G., Rosser, N. J., & Brain, M. J. (2022). An investigation of the combined effect of rainfall and road cut on landsliding. *Engineering Geology*, *307*(May), 106787. https://doi.org/10.1016/j.enggeo.2022.106787

Prakash, S., Mitra, A. K., Pai, D. S., & AghaKouchak, A. (2016). From TRMM to GPM: How well can heavy rainfall be detected from space? *Advances in Water Resources*, *88*, 1–7. https://doi.org/10.1016/j.advwatres.2015.11.008

Press, S. (2018). *Bibliometric Analysis of Global Research Progress on Coastal Flooding*. *28*(6), 998–1008.

Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science*, *6*(2), 177–202. https://doi.org/10.1007/s11625-011-0129-1

R Core Team. (2022). *R: A Language and Environment for Statistical computing.* R Foundation for Statistical Computing. https://www.r-project.org/

Raju, E., Boyd, E., & Otto, F. (2022). Stop blaming the climate for disasters. *Communications Earth and Environment*, *3*(1), 21–22. https://doi.org/10.1038/s43247-021-00332-2

Ran, J., MacGillivray, B. H., Gong, Y., & Hales, T. C. (2020). The application of frameworks for measuring social vulnerability and resilience to geophysical hazards within developing countries: A systematic review and narrative synthesis. *Science of the Total Environment*, *711*, 134486. https://doi.org/10.1016/j.scitotenv.2019.134486

Ran, Q., Su, D., Li, P., & He, Z. (2012). Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion. *Journal of Hydrology*, *424–425*, 99–111. https://doi.org/10.1016/J.JHYDROL.2011.12.035

Reaney, S. M. (2022). Spatial targeting of nature-based solutions for flood risk management within river catchments. *Journal of Flood Risk Management*, *15*(3), 0–12. https://doi.org/10.1111/jfr3.12803

Reason, J. (1990). Human error. In *International Journal of Man-Machine Studies* (Vol. 39). https://doi.org/10.7748/ns.11.49.20.s36

Rigg, J., Oven, K. J., Basyal, G. K., & Lamichhane, R. (2016). Between a rock and a hard place: Vulnerability and precarity in rural Nepal. *Geoforum*, *76*, 63–74. https://doi.org/10.1016/j.geoforum.2016.08.014

Roberts, S., Jones, J. N., & Boulton, S. J. (2021). Characteristics of landslide path dependency revealed through multiple resolution landslide inventories in the Nepal Himalaya. *Geomorphology*, *390*. https://doi.org/10.1016/J.GEOMORPH.2021.107868

Rufat, S., Tate, E., Burton, C. G., & Maroof, A. S. (2015). Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction*. https://doi.org/10.1016/j.ijdrr.2015.09.013

Ruiz-Villanueva, V., Allen, S., Arora, M., Goel, N. K., Stoffel, M., & Ch, D. (2017).

Recent catastrophic landslide lake outburst floods in the Himalayan mountain range. *Progress in Physical Geography*, *41*(1), 3–28. https://doi.org/10.1177/0309133316658614

Samir, K. C. (2013). Community vulnerability to floods and landslides in Nepal. *Ecology and Society*, *18*(1). https://doi.org/10.5751/ES-05095-180108

Santha, S. D., & Sreedharan, R. K. (2010). Population vulnerability and disaster risk reduction: A situation analysis among the landslide affected communities in Kerala, India. *Jàmbá: Journal of Disaster Risk Studies*, *3*(1), 367–380. https://doi.org/10.4102/jamba.v3i1.36

Schilling, J., Vivekananda, J., Khan, M. A., & Pandey, N. (2013). Vulnerability to Environmental Risks and Effects on Community Resilience in Mid-West Nepal and South-East Pakistan. *Environment and Natural Resources Research*, *3*(4), 27–45. https://doi.org/10.5539/enrr.v3n4p27

Segoni, S., Piciullo, L., & Gariano, S. L. (2018). A review of the recent literature on rainfall thresholds for landslide occurrence. *Landslides*, *15*(8), 1483–1501. https://doi.org/10.1007/s10346-018-0966-4

Shen, P., Zhang, L., Chen, H., & Fan, R. (2018). EDDA 2.0: integrated simulation of debris flow initiation and dynamics considering two initiation mechanisms. *Geosci. Model Dev*, *11*, 2841–2856. https://doi.org/10.5194/gmd-11-2841-2018

Shrestha, M. L. (2000). Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, *75*(1–2), 21–28. https://doi.org/10.1007/s007030070012

Shrestha, M. S. (2002). Flood Risk and Vulnerability Mapping Usng Gis : a. *Development*, 1–10.

Shrestha, M. S., Gurung, M. B., Khadgi, V. R., Wagle, N., Banarjee, S., Sherchan, U., Parajuli, B., & Mishra, A. (2021). The last mile: Flood risk communication for better preparedness in Nepal. *International Journal of Disaster Risk Reduction*, *56*(June 2019), 102118. https://doi.org/10.1016/j.ijdrr.2021.102118

Simkhada, P. P., Regmi, P. R., van Teijlingen, E., & Aryal, N. (2017). Identifying the gaps in Nepalese migrant workers' health and well-being: A review of the literature. *Journal of Travel Medicine*, *24*(4), 1–9. https://doi.org/10.1093/jtm/tax021

Simmonds, R., White, C. J., Douglas, J., Sauter, C., & Brett, L. (n.d.). *A review of interacting natural hazards and cascading impacts in Scotland Research funded by the National Centre for Resilience*.

Skilodimou, H. D., Bathrellos, G. D., Chousianitis, K., Youssef, A. M., & Pradhan, B. (2019). Multi-hazard assessment modeling via multi-criteria analysis and GIS: a case study. *Environmental Earth Sciences*, *78*(2), 47. https://doi.org/10.1007/s12665-018-8003-4

Smith, P. J., Brown, S., & Dugar, S. (2017). Community-based early warning systems for flood risk mitigation in Nepal. *Hazards Earth Syst. Sci*, *17*, 423–437. https://doi.org/10.5194/nhess-17-423-2017

Sneddon, A. (2019). *Resilience to Changing Risk*. *2018*, 2018–2019.

Stanley, T., Kirschbaum, D. B., Pascale, S., & Kapnick, S. (2020). Extreme precipitation in the Himalayan landslide hotspot. *Advances in Global Change Research*, *69*(April), 1087–1111. https://doi.org/10.1007/978-3-030-35798-6_31

Stewart, I. D. (2011). *A systematic review and scientific critique of methodology in modern urban heat island literature*. *217*(April 2010), 200–217. https://doi.org/10.1002/joc.2141

Sudmeier-Rieux, K., Jaquet, S., Derron, M. H., Jaboyedoff, M., & Devkota, S. (2012). A case study of coping strategies and landslides in two villages of Central-Eastern Nepal. *Applied Geography*, *32*(2), 680–690. https://doi.org/10.1016/j.apgeog.2011.07.005

Sudmeier-Rieux, K., Mcadoo, B. G., Devkota, S., Chandra, P., Rajbhandari, L., Howell, J., & Sharma, S. (2019). Invited perspectives: Mountain roads in Nepal at a new crossroads. *Hazards Earth Syst. Sci*, *19*, 655–660. https://doi.org/10.5194/nhess-19-655-2019

Sugden, F., de Silva, S., Clement, F., Maskey-Amatya, N., Ramesh, V., Philip, A., & Bharati, L. (2014). A framework to understand gender and structural vulnerability to climate change in the Ganges River Basin: Lessons from Bangladesh, India and Nepal. In *IWMI Working Papers* (Vol. 159). https://doi.org/10.5337/2014.230

Sugden, F., Maskey, N., Clement, F., Ramesh, V., Philip, A., & Rai, A. (2014). Agrarian stress and climate change in the Eastern Gangetic Plains: Gendered vulnerability in a stratified social formation. *Global Environmental Change*, *29*, 258–269. https://doi.org/10.1016/j.gloenvcha.2014.10.008

Sullivan-Wiley, K. A., & Short Gianotti, A. G. (2017). Risk Perception in a Multi-Hazard Environment. *World Development*, *97*, 138–152.

https://doi.org/10.1016/j.worlddev.2017.04.002

Swapan, M. S. H., & Sadeque, S. (2021). Place attachment in natural hazard-prone areas and decision to relocate: Research review and agenda for developing countries. *International Journal of Disaster Risk Reduction*, *52*(April 2020), 101937. https://doi.org/10.1016/j.ijdrr.2020.101937

Talchabhadel, R., Karki, R., Thapa, B. R., Maharjan, M., & Parajuli, B. (2018). Spatio-temporal variability of extreme precipitation in Nepal. *International Journal of Climatology*, *38*(11), 4296–4313. https://doi.org/10.1002/joc.5669

Thapa, P., & Thapa, N. (2021). Floods Risk Mapping and Assessing Vulnerability of Morang, Nepal. *ResearchSquare*, 1–8. https://doi.org/10.21203/rs.3.rs-150717

Thapa, S., Shrestha, A., Lamichhane, S., Adhikari, R., & Gautam, D. (2020). Catchment-scale flood hazard mapping and flood vulnerability analysis of residential buildings: The case of Khando River in eastern Nepal. *Journal of Hydrology: Regional Studies*, *30*(June), 100704. https://doi.org/10.1016/j.ejrh.2020.100704

Turconi, L., Tropeano, D., Savio, G., De, S. K., & Mason, P. J. (2015). Landscape analysis for multi-hazard prevention in Orco and Soana valleys, Northwest Italy. *Natural Hazards and Earth System Sciences*, *15*(9), 1963–1972. https://doi.org/10.5194/nhess-15-1963-2015

Twigg, J., Cannon, T., Cannon, T., Twigg, J., Rowell, J., & Cannon, T. (2003). *Social Vulnerability , Sustainable Livelihoods and Disasters Social Vulnerability , Sustainable Livelihoods Sustainable Livelihoods Support Office See below for updated contact Contact point :*

UNDRR. (2022). *Download DesInventar Open Source Software*. https://www.desinventar.net/download.html

UNISDR. (2015). *Sendai Framework for Disaster Risk Reduction*. http://www.unisdr.org/we/coordinate/sendai-framework

Uprety, M., Ochoa-Tocachi, B. F., Paul, J. D., Regmi, S., & Buytaert, W. (2019). Improving water resources management using participatory monitoring in a remote mountainous region of Nepal. *Journal of Hydrology: Regional Studies*, *23*, 100604. https://doi.org/10.1016/j.ejrh.2019.100604

Van Loon, A. F., & Laaha, G. (2015). Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*, *526*, 3–14. https://doi.org/10.1016/J.JHYDROL.2014.10.059

van Westen, C., Kappes, M. S., Luna, B. Q., Frigerio, S., Glade, T., & Malet, J. P. (2014). Medium-scale multi-hazard risk assessment of gravitational processes. In *Advances in Natural and Technological Hazards Research* (Vol. 34). https://doi.org/10.1007/978-94-007-6769-0_7

van Westen, C., Kappes, M. S., Quan Luna, B., Frigerio, S., Glade, T., Malet, J.-P., Kappes, M., Quan Luna Det Norske Veritas, B., Frigerio, N. S., & Malet, J. (2014). *Mountain Risks: From Prediction to Management and Governance*. *34*. https://doi.org/10.1007/978-94-007-6769-0

Vij, S., Russell, C., Clark, J., Parajuli, B. P., Shakya, P., & Dewulf, A. (2020). Evolving disaster governance paradigms in Nepal. *International Journal of Disaster Risk Reduction*, *50*(May), 101911. https://doi.org/10.1016/j.ijdrr.2020.101911

Vuillez, C., Tonini, M., Sudmeier-Rieux, K., Devkota, S., Derron, M. H., & Jaboyedoff, M. (2018). Land use changes, landslides and roads in the Phewa Watershed, Western Nepal from 1979 to 2016. *Applied Geography*, *94*(March 2017), 30–40. https://doi.org/10.1016/j.apgeog.2018.03.003

Wang, Y., Gardoni, P., Murphy, C., & Guerrier, S. (2021). Empirical Predictive Modeling Approach to Quantifying Social Vulnerability to Natural Hazards. *Annals of the American Association of Geographers*, *111*(5), 1559–1583. https://doi.org/10.1080/24694452.2020.1823807

Weichselgartner, J. (2001). Disaster mitigation: The concept of vulnerability revisited. *Disaster Prevention and Management: An International Journal*, *10*(2), 85–94. https://doi.org/10.1108/09653560110388609

Wilson, B. S. (2019). Overrun by averages: An empirical analysis into the consistency of social vulnerability components across multiple scales. *International Journal of Disaster Risk Reduction*, *40*(November 2018), 101268. https://doi.org/10.1016/j.ijdrr.2019.101268

Wisner, B. (2004). *At risk : natural hazards, people's vulnerability, and disasters*. Routledge. https://books.google.co.uk/books?hl=en&lr=&id=3CA8mT0vLFgC&oi=fnd&pg=PR9&dq=Blaikie&ots=hQZSFm5fhf&sig=0KJ3vVJmEmKKgsc-krbhmOY7rIM#v=onepage&q=Blaikie&f=false

World Bank. (2018). *World bank 2018-2019 country classifications*. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

Xu, L., Gober, P., Wheater, H. S., & Kajikawa, Y. (2018a). *Reframing socio-hydrological research to include a social science perspective*. *563*(May), 76–83. https://doi.org/10.1016/j.jhydrol.2018.05.061

Xu, L., Gober, P., Wheater, H. S., & Kajikawa, Y. (2018b). Reframing socio-hydrological research to include a social science perspective. *Journal of Hydrology*, *563*, 76–83. https://doi.org/10.1016/j.jhydrol.2018.05.061

Yousefi, S., Pourghasemi, H. R., Emami, S. N., Pouyan, S., Eskandari, S., & Tiefenbacher, J. P. (2020). A machine learning framework for multi-hazards modeling and mapping in a mountainous area. *Scientific Reports*, *10*(1), 1–14. https://doi.org/10.1038/s41598-020-69233-2

Zêzere, J. L., Vaz, T., Pereira, S., Oliveira, S. C., Marques, R., & Garcia, R. A. C. (2015). Rainfall thresholds for landslide activity in Portugal: a state of the art. *Environmental Earth Sciences*, *73*(6), 2917–2936. https://doi.org/10.1007/s12665-014-3672-0

Zhang, K., Wang, S., Bao, H., & Zhao, X. (2019). Characteristics and influencing factors of rainfall-induced landslide and debris flow hazards in Shaanxi Province, China. *Natural Hazards and Earth System Sciences*, *19*(1), 93–105. https://doi.org/10.5194/nhess-19-93-2019

Zhou, Y., Su, Q., Li, Y., & Li, X. (2022). *Spatial-Temporal Characteristics of Multi-Hazard Resilience in Ecologically Fragile Areas of Southwest China : A Case Study in Aba*.

Zogheib, C., Ochoa-tocachi, B. F., Paul, J. D., & Hannah, D. M. (n.d.). *Exploring a water data , evidence , and governance theory*.

Zogheib, C., Ochoa-tocachi, B. F., Paul, J. D., & Hannah, D. M. (2018). *Exploring a water data , evidence , and governance theory*.

# Appendix

Progress in Physical Geography
2020, Vol. 44(2) 267–284

DOI: 10.1177/0309133319900926
journals.sagepub.com/home/ppg
SAGE

# A framework for understanding water-related multi-hazards in a sustainable development context

**Julia M Docherty**
University of Birmingham, UK

**Feng Mao**
University of Birmingham, UK

**Wouter Buytaert**
Imperial College London, UK

**Julian RA Clark**
University of Birmingham, UK

**David M Hannah**
University of Birmingham, UK

**Abstract**

Hazards often do not occur in isolation and, for this reason, a multi-hazard approach is vital in realising their impact and providing solutions for disaster risk reduction and sustainable development. We present a novel framework that emerges from a bibliometric analysis of the multi-hazard literature and a critical appraisal of the existing approaches. It was found that multi-hazard research has expanded greatly over the last 20 years, furthering our understanding of the subject with important applications in risk assessment and management. These studies have contextualised multi-hazards, developed models and frameworks to analyse them, provided case studies to test multi-hazard-based approaches and produced reviews. It was found that landslides and floods are the most frequently co-occurring hazards within the bibliographic dataset, yet understanding of their interactions, hydrometeorological drivers and landscape controls remains poorly conceptualised. Therefore, we propose a new framework for investigating water-related multi-hazards that leverages and synthesises existing methods to address the challenges identified to date. We also find a geographical bias, with less multi-hazard research in lower- and middle-income countries and remote environments due to data scarcity and limited accessibility. Our framework therefore includes the ability to address geographically specific key considerations including available and accessible data, community variability and cross-sectoral collaborations. In doing so it offers guidance on structuring future analyses to improve our understanding of multi-hazards, reduce disaster risk, increase community resilience and make progress towards sustainable development.

**Corresponding author:**
Julia M Docherty, School of Geography Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, UK.
Email: JMD792@bham.ac.uk

**Keywords**
Multi-hazards, disaster risk reduction, sustainable development, bibliometric analysis

## I Introduction

Natural hazards have devastating economic, societal and environmental impacts around the globe (UNISDR, 2015). It has become widely accepted that hazards do not occur in isolation and this realisation is vital in furthering our understanding of natural hazards (Gill and Malamud, 2014). Multi-hazard research is the study of multiple hazards and their interactions within a defined time and space (Kappes et al., 2012). Hewitt and Burton (1973) first proposed the concept of investigating all hazards and environmental parameters within a hazardous environment, followed over a decade later by Lewis (1984), who used the term 'multi-hazard' in the analysis of hazards, namely the combination of earthquakes, droughts and hurricanes in Antigua. These papers set the foundation for a holistic approach to multi-hazard research, in which both environmental and socio-economic parameters are considered. Through time, multi-hazard research has evolved with valuable contributions made from several disciplinary perspectives. In more recent years, the social vulnerability of affected populations has been included in the assessment and management of natural disasters (Blaikie et al., 1994; Cutter, 1996). This research has resulted in an extensive literature, emphasising the need to consolidate findings and identify gaps in existing research through meta-analysis.

Crucial here is enhancing our knowledge of multi-hazards given their role in exacerbating development challenges faced by low- and middle-income countries. These challenges are often intensified by the impacts of intersecting natural hazards, meaning that progress towards achieving the United Nations' Sustainable Development Goals must involve a comprehensive understanding of multi-hazards, as outlined in the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015). Lower- and middle-income countries (LMICs) are impacted most heavily due to high levels of vulnerability related to poverty, inequality and illiteracy, in addition to the challenges presented within evolving governance systems (Keating et al., 2017). Furthermore, in LMICs, there is a lack of resources and training, which restricts the quantity and quality of data obtainable (Johnson et al., 2018; Zogheib et al., 2018). This data shortage leads to a paucity in knowledge and understanding (Barrantes, 2018; Uprety et al., 2019).

The threat of climate change further exacerbates these uncertainties, in particular highlighting the increasing dangers of hazards related to hydrometeorology (Gallina et al., 2016; Hannah et al., 2005). Water-related hazards, such as hydrologically induced landslides and flooding, are among the most destructive of these hazard types (Emerton et al., 2016; Shen et al., 2018). A better understanding of water-related multi-hazards is thus vital for implementing effective evidence-based policies for disaster risk reduction, an issue that is particularly pertinent in LMICs (Mignan et al., 2017). However, notwithstanding these geographically defined effects, the fact remains that existing multi-hazard frameworks often fail in characterising the space- and time-dependent dynamics of the environment and do not always consider the people and places that are affected (Haughton and White, 2018; Pescaroli and Alexander, 2018). Consequently, we argue that it is vital to develop innovative approaches to analysing multi-hazards capable of comprehensively investigating water-related multi-hazards in data-scarce regions of LMICs.

This paper aims to progress physical geographic research by yielding valuable knowledge on the current state of work using the term 'multi-hazard', in line with the call for a

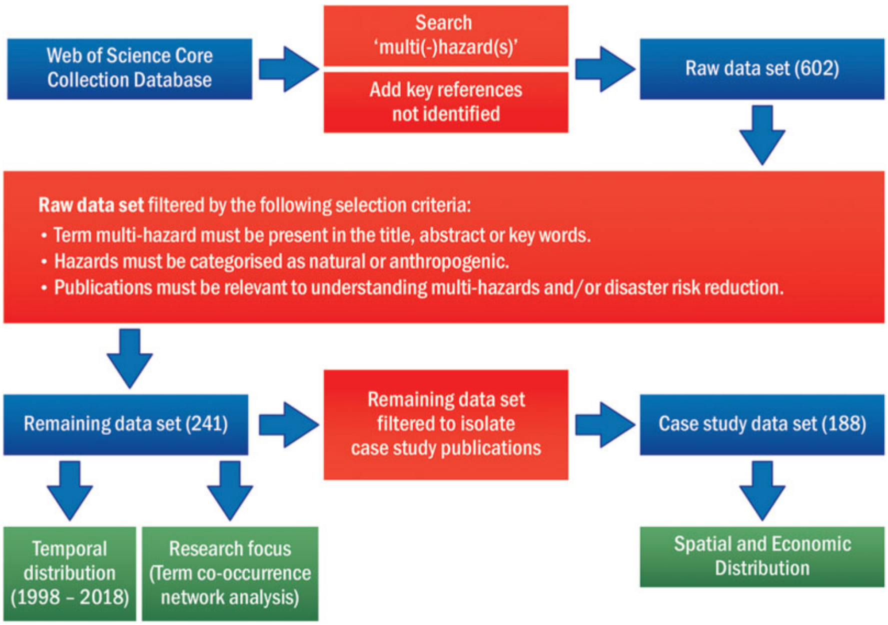


**Figure 1.** Schematic flow diagram of the selection of bibliometric data sets and analysis. The blue boxes indicate data sets, the red boxes are actions taken to filter those data and the green boxes show the analysis.

multi-hazard approach in the SFDRR. We have undertaken this task through a structured bibliometric analysis, which provides insights and identifies trends and gaps within a defined literary sample by classifying publications according to factors such as distributions, focus and authorship (Gao and Ruan, 2018).

The results of these investigations underpin the development of an innovative framework that seeks to advance understanding of multi-hazards in a sustainable development context. Our framework is novel in that it takes a place-based approach to address the full complexity of a multi-faceted system and unites theories and methodologies from differing perspectives and skillsets, overcoming the challenges and limitations of multi-hazard research.

## II Data and methods

For the paper, bibliometric analysis techniques, adapted from previous studies, were applied in order to understand the scope and evaluate trends in the multi-hazard research (cf. Karpouzoglou et al., 2016; Stewart, 2011; Xu et al., 2018). The literature was distilled to provide a representative sample and analysed according to application and orientation, collaborative networks and their temporal, spatial, economic and environmental distribution (see Figure 1). The spatial, economic and environmental distribution were investigated to discover areas that have been less intensively studied, whilst term co-occurrence maps were used to analyse the focal topics of the research. The outcomes of this analysis provide the evidence base to re-think and focus a new framework.

The *Web of Science Core Collection* database was used to find the available academic literature in the area of multi-hazard research. The initial search used the term '*multi(-)hazard(s)*' in the topic of the publications and generated a raw data set of 602 results, starting with the first paper to mention multi-hazards (Lewis, 1984), extending to 2018, the most recent at the time of the search (data accessed 14 January 2019). The results were read, evaluated and filtered according to a set of selection criteria; publications were only included if the term multi-hazard was present in the title, abstract and/or keywords, the hazards mentioned could be categorised as natural or anthropogenic, and the publications were relevant to understanding multi-hazards and/or disaster risk reduction. From the raw data, 60% of publications were excluded as they were related to healthcare, social care, terrorism and infrastructure reinforcement. Additional key references in the field, not identified through the initial search but highly cited within the remaining publications, were added subsequently following the methods of Karpouzoglou et al. (2016). This included Hewitt and Burton (1971), a highly cited paper describing the concept of 'all hazards at a place' without using the term 'multi-hazard', and a number of highly cited papers using the synonyms cascading and/or compound hazards. This protocol narrowed the dataset to publications specific to this study and key to developing a new framework for disaster risk reduction.

The resulting 241 papers formed the bibliographic data set, which was first analysed according to temporal distribution. The number of publications through time, based on the year of publication, was plotted to investigate the temporal trend from 1998–2018. This timeframe was selected because only two articles were published before 1998, namely Hewitt and Burton (1971) and Lewis (1984). These have not been included in this sample due to the sparse level of publication between 1971 and 1998 as single hazard approaches were dominating the field.

Of the 241 publications, 188 were research articles set in specific case-study locations. The 53 remaining publications included comparative studies, broad-scale global analysis and conceptual review papers. Case studies were identified individually by finding and noting references to study locations and also the location of the institute conducting the research. This generated data to analyse the spatial distribution and economic level of the case-study areas and a comparison with where the researchers had published. The level of economic development of each country was based on the World Bank 2018–2019 country classifications (World Bank, 2018). The information on study location was coupled with the location of publication to evaluate global North to global South distributions in research.

The bibliographic data set of 241 papers was also analysed according to overall focal topic. This was done by creating a term co-occurrence map based on text data, generated using VOSviewer version 1.6.9 (van Eck and Waltman, 2018). The minimum number of occurrences of a term was set to 10 and of the 15,080 terms detected, 237 met this threshold. Irrelevant terms, such as case-study locations, highly cited author names, journal titles and words present in all texts were filtered before the map was generated.

In addition to finding these trends, the identified literature was also critically analysed to evaluate the key themes, major challenges and existing approaches. The literature attributes from nine highly cited publications were identified and displayed in table form. The analysis of this data using the methods stated was intended to provide a comprehensive overview of the multi-hazard literature and identify the challenges and key considerations for developing a framework.

## III Bibliometric analysis and interpretation

### *3.1 Spatial and temporal distribution*

Figure 2 shows the temporal distribution of publications related to understanding multi-hazards and disaster risk reduction between 1998 and 2018. We find an overall increasing trend over this 20-year period characterised by a slow

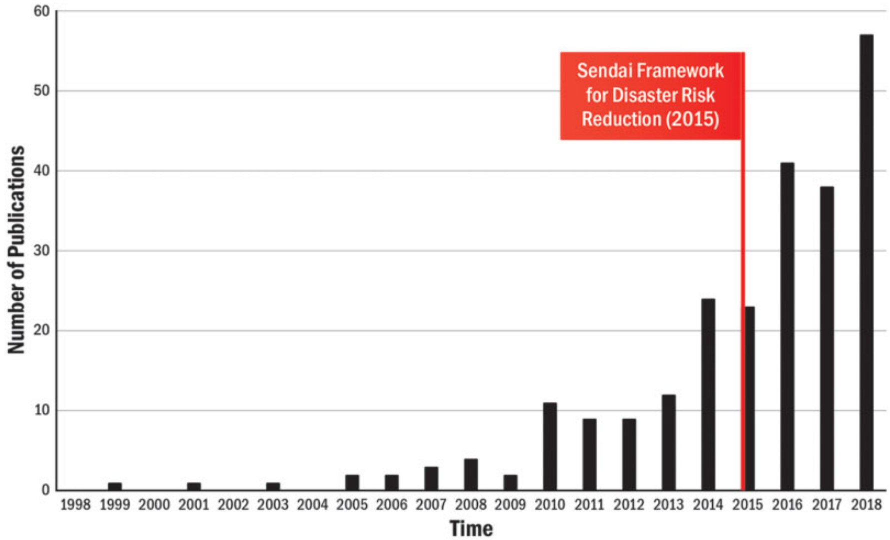


**Figure 2.** Temporal distribution of reviewed multi-hazard publications.
The red bar shows the Sendai Framework for Disaster Risk Reduction (SFDRR).

progression between 1998 and 2010, followed by a gradual increase. This is a significant trend, taking into account that the total number of publications has also increased through time. The scientific community gradually began to focus on multi-hazards from around 2003, then Kappes et al. (2012) defined the term multi-hazard, which made a significant impact on the temporal distribution of the literature (Figure 2). The introduction in 2015 of the SFDRR, which calls for a 'multi-hazard' approach in relation to disaster risk reduction, may have had some impact on increasing multi-hazard publications, although a marked change is not evident (Figure 2). In 2018 alone, 57 articles were published related to understanding multi-hazards and disaster risk reduction.

We identify several reasons for the increase in the number of publications on this topic over the past 20 years, indicating the increasing recognition and importance of investigating multi-hazard environments. Climate change, increasing climate variability and the occurrence of extreme events linked often to the devastation of human environments has encouraged research on natural hazards (Sullivan-Wiley and Short Gianotti, 2017). In addition, over time, there has been increased understanding that hazards do not tend to act in isolation and thus a multi-hazard approach is required. This has been internationally recognised and published in strategy and policy documents, including the SFDRR (UNISDR, 2015).

Analysing the spatial distribution of multi-hazard case studies shows that the highest density is in Europe, representing 30% of all studies (Figure 3). The countries with the highest total number of case studies are China, USA, Italy and India. Further analysis of the localities shows the majority of research has taken place in higher-income countries (HICs) rather than those with a lower income (Figure 3). Authorship analysis showed that in 66% of the publications the area studied is in the same country as the institute of the first author. This indicates that research has tended to be conducted by local researchers, due to the low cost of local fieldwork, rather than an international focus

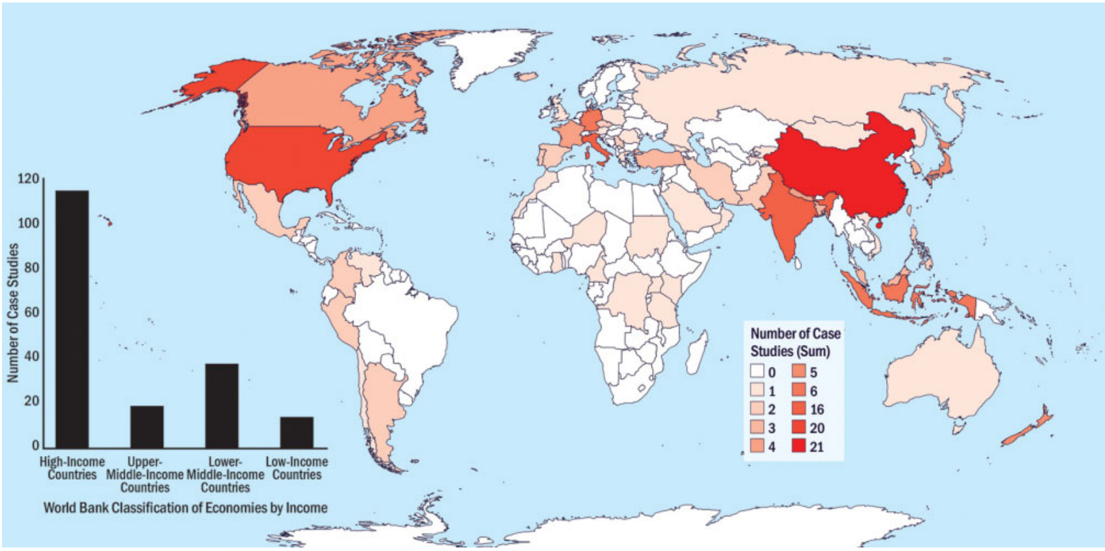


**Figure 3.** Spatial distribution of multi-hazard case studies and chart of case studies by level of economic development.
The countries were classified according to the World Bank 2018–2019 as high-income, upper-middle-income, lower-middle-income.

from countries in the global North on countries in the global South.

This analysis shows that multi-hazard environments in HICs have been studied more intensively than those in LMICs. Our analysis suggests that this is because in HICs more numerous reliable data are available and it is easier to access remote areas and conduct fieldwork for sourcing primary data (Petley, 2010). Thus, we argue that we need to balance the spatial distribution of multi-hazard research and ensure that the understanding of hazard-prone environments in LMICs is not limited by access to and availability of data.

In addition, channels of communication between citizens and authorities are better developed in HICs, resulting in a greater response to knowledge generated for disaster risk reduction (McCallum et al., 2016). These data-intensive and cooperative systems have enabled most communities in HICs to develop strategies for coping with natural hazards and build resilience for effective recovery. This must be a priority outcome for the development of a framework focused on remote data-scarce regions of LMICs.

## 3.2 Focal topics

Analysis of the occurrence of frequently used terms within the text data is useful for realising the key focal topics within the refined literature. Figure 4 shows a term co-occurrence network diagram and a chart of the most frequently occurring hazard terms based on text data from the refined data set. The colours on the diagram show three distinct clusters of related terms. In red, we have key quantitative methods and techniques for addressing disaster risk reduction, namely 'Geographical Information Systems (GIS)', 'remote sensing', 'probability', 'model' and 'mapping', which have strong linkage with the hazards 'volcano' on one side and 'tsunami' and 'storm surge' on the other. At the top of the diagram, the blue cluster with multiple linkages across the figure sets out instrumental hazard terms 'earthquake',

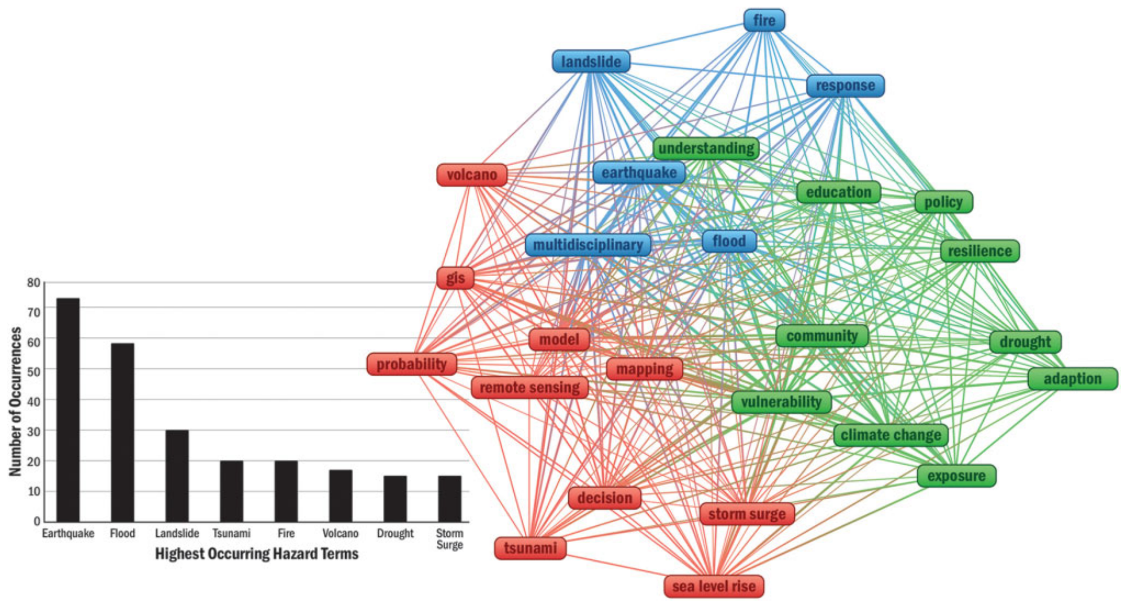


**Figure 4.** Term co-occurrence network diagram based on text data and chart of the most frequently occurring hazard terms.
The boxes represent frequently occurring terms and the lines that link the nodes represent the co-occurrence of terms within publications. The different colours show the clustering of related terms.

'landslide', 'flood' and 'fire', which are strongly linked to 'multidisciplinary' and 'response'. On the right-hand side of the diagram there is a green cluster that highlights critical social themes including 'education', 'understanding', 'community', 'vulnerability', 'resilience', 'exposure' and 'adaptation'. Within this green cluster, 'climate change' and 'drought' are highly linked with these themes.

Investigation of the occurrence of individual hazard terms at a minimum of five occurrences showed that the terms 'earthquake', 'flood' and 'landslide' had the highest number of occurrences and were closely related. The terms 'flood' and 'landslide' have the highest total link strength, which means that they often occur in the same articles. This indicates that much of the multi-hazard literature focuses on these hazards and regions where they are both present.

The focal topics of the bibliographic data therefore fall into different disciplines and categories. We argue that all of these themes are important to disaster risk reduction, and they must be brought together and considered from the outset in the development of our framework. Furthermore, this analysis has highlighted the importance of topics falling within social science research such as 'education', 'community' and 'vulnerability'.

Hazard term analysis has highlighted that hydrometeorological processes, specifically landslides and flooding, were highly occurring hazards and strongly linked. Landslides and flooding have a strong linkage because they have factors in common. They occur side by side in mountainous regions and often affect the same populations. The combined force of these two hazards leads to the highest level of economic damage and mortality (Shen et al., 2018). Both hazards are driven by heavy precipitation and controlled by the landscape characteristics, yet there remains a poor understanding of the direct correlation and information on how they interact (Allen et al., 2016). Climate change is associated with more severe weather events, which is likely to increase the number of events and devastation caused by flooding and hydrologically induced mass movements in the future. We argue that it is necessary to better understand the processes related to landslides and flooding in order to mitigate this risk. Thus, we have focused our framework on understanding water-related multi-hazards.

Water-related hazards are most often driven by intense and/or prolonged rainfall whilst moderated by site-specific basin characteristics (Devkota et al., 2014; Kirschbaum et al., 2012). The critical analysis also found that there were many publications focused on the distribution of landslide events and the thematic grouping of different types of mass movements in which flooding did not feature (Chen et al., 2016; Galli et al., 2008). In some cases this was because one event occurred without the other, as is the case in many regions such as parts of the Alps and Pyrenees (Papathoma-Köhle et al., 2011; Turconi et al., 2015). Van Westen et al. (2014) effectively group and analyse rock falls, debris flows, surficial landslides and slow-moving landslides separately. This has a significant impact on our understanding of multi-hazards and implications for disaster risk reduction, and therefore must also be a consideration within our framework.

Much of the research centred around landslide-prone areas of south Asia focuses predominantly on landslide risk (Berti et al., 2012; Kirschbaum et al., 2012; Petley et al., 2007). Within these complex systems, antecedent rainfall accumulation and previous hazard occurrence can be responsible for priming more hazards (Ruiz-Villanueva et al., 2017), for example, the gravitational mass-movement of water-logged slopes, slope instability caused by undercutting by floodwaters and sediment-dammed landslide lake outburst floods (Allen et al., 2016). Other significant drivers include earthquake occurrence, over-grazing and vegetation removal, land-use change and the construction of infrastructure such as roads (Dai et al., 2002; Sudmeier-Rieux et al., 2019). There is a gap in the literature in which to explore the co-occurrence of both landslides and floods and a new framework is required to further our knowledge by identifying rainfall signatures driving these multi-hazards and evaluate the extent to which basin characteristics moderate the landscape response.

### *3.3 Literature attributes*

Attributes of the literature were analysed according to a set of comparison criteria. Tables 1 and 2 display this analysis, with five examples of the most highly cited review papers (Table 1) and four examples of highly cited case studies from the multi-hazard literature (Table 2).

The approaches to multi-hazard research have been reviewed extensively (Gill and Malamud, 2014; Kappes et al., 2012; Pescaroli and Alexander, 2018). It was found that all the review papers in Table 1 call for an integrated multi-hazard approach or have the potential for this approach to be applied. The selection of example review papers range in their focus from Blaikie et al. (1994) and Cutter (1996), in which social vulnerability is given an equal importance to the geographic context, to Kappes et al. (2012) and Gill and Malamud (2014), which focus more on the quantitative methods of understanding hazard interactions.

Kappes et al. (2012) focus multi-hazard research on an all-inclusive examination of the whole range of natural hazards present. Gill and Malamud (2014) provide a network for visualising cascading interactions between 21 natural hazards. These include earthquake, tsunami, volcanic eruption, landslide, snow avalanche, flood, drought, regional subsidence, ground collapse, soil (local) subsidence, ground heave, storm, tornado, hailstorm, snowstorm, lightning, extreme temperature (hot), extreme temperature

**Table 1.** Literature attributes table comparing key multi-hazard reviews using a set of comparison criteria.

| Multi-hazard review | Recommended approach to multi-hazards | Methods or model applied | Strengths and challenges |
|---|---|---|---|
| Blaikie et al. (1994) | Potential multi-hazard application | 'Disaster pressure and release' model. | Recognises and outlines that there is both a socio-economic and natural side to disasters.<br>Does not outline multi-hazard approach, yet has potential to be applied to multiple hazards. |
| Cutter (1996) | Potential multi-hazard application | 'The hazards of place' model of vulnerability. | Considers hazard potential from geographical context and social vulnerability.<br>Although facilitating multi-hazard approaches, there is no insight into multiple hazard interactions. |
| Kappes et al. (2012) | Integrated multi-hazard | Examining hazard interactions through binary and descriptive matrices. | Defines and calls for an integrated multi-hazard approach.<br>Does not consider people and place, although has the potential to be applied to multidisciplinary frameworks for understanding multi-hazards. |
| Gill and Malamud (2014) | Integrated multi-hazard | Identification and visualisation of hazard interactions. | Supports a wider understanding of interactions, although is restricted to sequential or cascading hazards.<br>Does not consider people and place, although has the potential to be applied to multidisciplinary frameworks for understanding multi-hazards. |
| Pescaroli and Alexander (2018) | Integrated multi-hazard | Scenario-building and vulnerability assessments.<br>Identification of thresholds/ tipping points. | Supports an understanding and visualisation of the build-up to high impact events considering societal consequences. |

(cold), wildfire, geomagnetic storm and impact event, which are divided into six major hazard groups, namely geophysical, hydrological, shallow earth processes, atmospheric, biophysical and space. This concept is explored further in Gill and Malamud (2017), in which 18 anthropogenic process types are combined into the matrix; examples include groundwater abstraction, material injection, vegetation removal, infrastructure construction, chemical explosion and fire. These more quantitative papers lack a social vulnerability component; however, the mathematical principles can be used in the application of a multidisciplinary framework for understanding multi-hazards. Pescaroli and Alexander (2018), in the most recent review, take a holistic approach and support an understanding and visualisation of the build-up to high impact events considering societal consequences.

In most circumstances, the key information required for disaster risk reduction is predictions of where, when and the magnitude of the hazard extent (Liu et al., 2018). GIS hazard maps are a useful tool for communicating the intensity and distribution of 'risky spaces' (Haughton and

**Table 2.** Literature attributes table comparing key multi-hazard case studies according to a set of comparison criteria.

| Multi-hazard case study | Location | Approach to multi-hazards | Methods or model applied | Strengths and challenges |
| --- | --- | --- | --- | --- |
| Hewitt and Burton (1971) | Ontario, Canada | Multi-layer single hazard | 'All hazards at a place'. Multi-hazard mapping. | Holistic approach to natural hazards in which human response is also incorporated. Provides good foundation although specific techniques are now dated. |
| Carreño et al. (2007) | Bogota, Colombia and Barcelona, Spain | Multi-layer single hazard | Multi-hazard assessment based on physical and socio-economic indicators. | Multidisciplinary evaluation that takes into account direct physical damage and social fragility to seismic hazard. Indicators are applied to single hazards and then combined, which does not allow for interactions/feedbacks between hazards. |
| Bathrellos et al. (2017) | Peloponnesus, Greece | Multi-layer single hazard | Multi-hazard susceptibility mapping. | Comprehensive spatial representation of multiple hazards, but does not consider the social fabric. Overlapping hazards opposed to understanding and representing hazard interactions in time and space. |
| Depietri and McPhearson (2018) | New York City, USA | Multi-layer single hazard | Multi-hazard vulnerability mapping with socio-economic indicators based on surveys and weighting from local expert opinion. | Strong contribution specific to urban developed multi-hazard situation. Overlapping hazards rather than integrated multi-hazard approach, therefore does not consider interactions/cascades between hazards. |

White, 2018). They provide a visual representation of hazard predictions that can be used for implementing policy (Carpignano et al., 2009). Furthermore, early warning systems inform people at risk of natural hazards in advance of an event, giving people time to prepare and/or evacuate. They are based on the identification of threshold criteria for failure, according to the Cumulative Act Effect Model (also known as the Swiss cheese model) (Reason, 1990). In this model, when multiple factors align in a specific way, a reaction, in this case a hazardous event, is likely to take place. Real-time and historical data sets can be used to identify the points at which the environmental and societal data reach a tipping point at which these events occur. These resources are important for building community resilience and disaster preparedness (Gautam and Dulal, 2013; Pei et al., 2014; Smith et al., 2017).

Hewitt and Burton and the other case-study papers outlined in Table 2 use multi-hazard mapping (Bathrellos et al., 2017; Carreño et al., 2007; Depietri and McPhearson, 2018). These provide an effective spatial representation to predict the timing and impacts of multiple hazards; however, this layering of multiple hazards does not promote an understanding of the complex interactions and cascades between hazards. A framework that supports an integrated multi-hazard approach, in which the feedbacks and interactions between hazards are understood, is needed.

The social vulnerability of the affected people must also be understood and analysed within a new framework according to existing analytical methods (Gautam, 2017; Shrestha et al., 2004). Blaikie et al. (1994) introduced the ‘pressure and release’ model, which explains the preliminary driving processes that give rise to vulnerability in hazardous settings, for example, exposure. Cutter (1996) builds upon this in the ‘hazards of place’ model, in which the social fabric is explored in more depth and related to the geographic context. In this model, the vulnerability is not fixed in time and can adjust according to changes in the risk, mitigation and context of the environmental hazards.

Concurrently, we argue that physical attributes of multi-hazard environments must be investigated alongside their interactions with people and place (Aksha et al., 2018; Cutter et al., 2008). The value of bringing the physical and social together in this way gains a better understanding of the actualisation of hazards as risky events for different social groups in particular places. Hazard mortality and level of economic damage can be used for spatially and temporally representing the intensity and frequency of hazards and how they correlate (Krishnan et al., 2019; Mysiak et al., 2018; Skilodimou et al., 2019). This can be combined with socio-vulnerability indexing from socio-economic and demographic data to better understand the relative vulnerability to environmental hazards (Cutter et al., 2003). On a broader scale, power relations, prevailing social structures, access to resources, political influences and socio-economic development of a place are all factors that underlie vulnerability to natural hazards and therefore must also be considered (Blaikie et al., 1994; Pescaroli and Alexander, 2016). In particular, a framework is required to build upon these place-based approaches and provide new insights into multi-cascading risky events like landslides and flooding.

## IV The need for an analytical framework

The preceding analysis strongly suggests that there is a need for developing an alternative framework for investigating water-related multi-hazards, based upon the identification of specific key factors. Bibliometric analysis and critical evaluation of the literature identified a growing focus on multi-hazard research and a shift towards multidisciplinary approaches in which the social vulnerability of the impacted people is given an equal platform to the drivers of hazards within the environment (Beccari, 2016; Birkmann et al., 2013; Cutter et al., 2003; Rufat et al., 2015). There were two significant research gaps identified. The first is that there is less multi-hazard research in LMICs and remote environments due to data scarcity and limited accessibility. The second is that there is a limited understanding of the interactions between water-related hazards, specifically landslides and flooding, their hydrometeorological drivers and the controlling landscape characteristics. Thus, the development of a new framework must build upon these multidisciplinary approaches with a fresh perspective on landslides and flooding, whilst addressing the challenges of work in remote data-scarce mountainous regions.

## V A multi-hazard framework

Drawing on the preceding analysis and focused on water, we propose a novel framework offering a comprehensive understanding of multi-hazards in a sustainable development context (Figure 5). The framework foresees contributions from multiple academics from varied disciplines, non-governmental aid organisations,

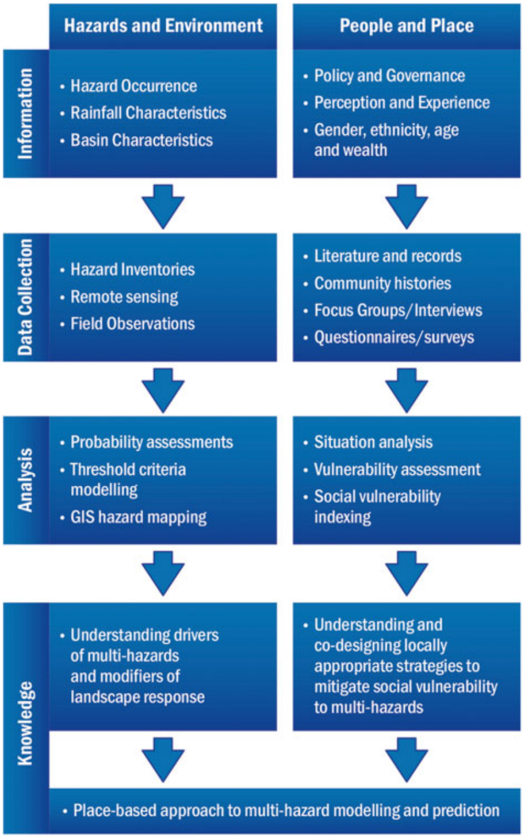


**Figure 5.** A schematic overview of the proposed framework for understanding water-related multi-hazards in a sustainable development context. The bullet points show respectively the information required, methods of collection, methods of analysis and the key knowledge questions that lead to our place-based approach to multi-hazard modelling and prediction. GIS: Geographical Information Systems.

national and local government bodies, impacted communities and other end-users. From the outset, both quantitative physical science and qualitative social science methods are combined to generate actionable knowledge for multi-hazard mitigation and adaptation.

The main pillars of the framework are parallel themes of ‘hazards and environment’ and ‘people and place’ that essentially encompass both quantitative and qualitative analytical methods of the driving forces of natural hazards and the risk that they pose. This relies on bringing together different data sources for analysis based on two key principles, namely understanding drivers of multi-hazards and modifiers of landscape response, and understanding and co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards. Addressing these different principles in a systematic and coordinated way gives a place-based approach to multi-hazard modelling and prediction. The framework components, described in the following, have emerged from the bibliometric analysis undertaken in this paper in which major gaps in the existing research were identified. We contend that the utilisation of this framework would lead to multiple benefits for disaster relief agencies, governments and communities directly affected by multi-hazards.

## *5.1 Hazards and environment*

This pillar involves contextualising the hazards and environmental parameters within the physical setting based on the obtainable data, focused on investigating hydrologically induced landslides and flooding.

In LMICs there is a need for advancing technologies for data collection and processing, such as low-cost sensors, public domain datasets and new Information and Communication Technologies (ICTs) (Abdulwahid and Pradhan, 2017; Kucera and Steinson, 2017; Zogheib et al., 2018). Our framework achieves this by developing and integrating information from various sources on multiple scales.

This pillar is broken down into ‘information’, ‘collection’ and ‘analysis’ sub-tasks using methods and techniques already widely used within the hazards literature (Allen et al., 2016; Dahal and Hasegawa, 2008).

Rainfall, the main driver of these systems, can be assessed according to various characteristics including magnitude, frequency, rainfall event duration and intensity, and the antecedent rainfall accumulation (Kansakar et al., 2004). For example, satellite rainfall products such as the Tropical Rainfall Measuring Mission (TRMM) can be openly accessed and used to analyse broad-scale rainfall distributions (Duncan and Biggs, 2012; Krakauer et al., 2013). Weather station data and rain gauges can be used to gather real-time high-resolution rainfall data, which can be used to calibrate these products and provide detailed analysis (Prakash et al., 2016). Hydrological data from rivers can be gathered using field observations, and river flow archives (where available) can be used to assess past hydrological variability (Hannah et al., 2011). Field and satellite observations can be taken to analyse the river basin controls, such as elevation, slope, river density and land cover. Time-lapse analysis of these images can be used to investigate changes in the floodplain, and slope vegetation and channel morphology. Hazard inventories based on satellite imagery and field mapping are used to account for the timing and spatial extent of natural hazards within the system (Adhikari et al., 2010; Kirschbaum et al., 2015).

The integration of this meteorological, hydrological, landscape and hazard information enables an understanding of the interactions and feedbacks between these water-related hazards, one of the gaps identified within existing multi-hazard frameworks during the bibliometric analysis. This understanding is necessary to support hazard prediction and GIS-based modelling.

## 5.2 People and place

We contend that 'people and place' must be given equal importance to 'hazards and environment', as shown in Figure 5. Specifically, the requirements and risk currencies of the impacted community and end-users must be considered from the outset and throughout the framework to ensure the outputs are useful, realistic and sustainable.

Concurrent with 'hazards and environment', this pillar is also broken down into 'information', 'collection' and 'analysis' using existing methods (Preston and Stafford-Smith, 2009).

At the national level, data should be obtained on disaster risk reduction policy, governance and societal structures from grey literature and government records. Community hazard resilience data can be accessed through qualitative methods such as situation analysis, which is the examination of a social situation, its elements and their relations, to provide a state of situation awareness for decision-makers and therefore greater adaptive capacity within the community (Roy, 2001). These methods include vulnerability and capacity assessments, which involve a combination of focus groups and community/household level interviews, questionnaires and surveys to collect information. Specific survey topics typically include contextual information about affected communities and the multiple hazards impacting them. The various risk currencies must also be assessed, which include factors such as human livelihoods, ownership of livestock and agricultural land, infrastructure provision, access to drinking water, communications, level of education, economy and environment.

As stated in the results of the bibliometric analysis, understanding the social situation in this way is vital for furthering our knowledge and making the research relevant and useful for vulnerable communities.

## 5.3 Knowledge

As noted previously, the proposed framework aims to yield information of direct practical relevance with potential to support decision-making for water-related natural disasters based around two key principles identified from bibliometric analysis, namely (a) understanding drivers of multi-hazards and modifiers of landscape response and (b) understanding and co-designing locally appropriate strategies to mitigate social vulnerability to multi-hazards.

This involves first evidencing the co-occurrence of water-related multi-hazards, then identifying hydrometeorological drivers and basin characteristics that modify those multi-hazards. This can then be combined with socio-economic data to construct statistical, GIS-based models to yield predictive multi-hazard vulnerability. This will improve our understanding of the interactions of water-related multi-hazards, their driving forces, the factors that determine sensitivity of landscapes and importantly the vulnerability of affected people. Prediction of multi-hazard scenarios is particularly key to this framework in an attempt to increase human preparedness and, thus, to increase the potential resilience of people and infrastructure.

In this way, the framework addresses the identified gaps in the existing research and provides new insights into coping with the challenges of work in remote data-scarce regions of LMICs. This framework is designed to be used on multiple scales, adapting to the spatial and temporal resolution of the available data. Hence, hypotheses can be developed at a broad scale by looking at large and long-term patterns from satellite data, which can then be tested by telescoping into areas in which there has been detailed groundwork.

In addition, the proposed framework copes with the communication challenges and supports a continual dialogue with stakeholders. Disaster risk reduction and progress in the sustainable development of vulnerable communities can only be achieved by engaging stakeholders and initiating a response to actionable knowledge. Therefore, effective communication between science and stakeholders is vital to this framework (Buytaert et al., 2014; Paton, 2008). The SFDRR stated the importance of 'society engagement' and the 'voluntary work of citizens' (UNISDR, 2015). This framework offers many opportunities for participatory approaches to knowledge generation. Leveraging new technologies, such as low-cost sensors in combination with smartphones and the internet, may allow community members to play pivotal roles in leading the measurement of environmental parameters, such as precipitation, river water and soil moisture levels. The participation of non-professional scientists in data collection, interpretation and analysis could increase the amount and quality of available data, whilst also engaging affected communities and promoting a better response to actionable knowledge (Paul et al., 2018). It also provides tools for local communities to address decisions related to disaster risk reduction in more socially equitable ways. This tackles the failures of existing 'top-down' governance models, common to LMICs, that depend on external interventions and are blind to the needs of marginal communities.

### *5.4 The benefits of this framework*

We argue that the utilisation of this framework has considerable potential to further understandings of hydrologically driven multi-hazard environments, most clearly by providing novel insight into how social vulnerability to these multi-hazards occurs within place. Thus, we envisage that by applying this framework, community awareness of the interconnections between hazards will be boosted, offering a platform for structuring the co-generation and sharing of knowledge, data and resources on locally specific multi-hazards. This platform function could be further enhanced through new data-gathering opportunities via low-cost sensor applications currently under development in hydrology, which seek to generate actionable knowledge for improving/refining multi-hazard forecasting capabilities (Mao et al., 2018). Such an approach has the potential to empower communities to respond more effectively to multi-hazards, reducing localised disaster risk, increasing community resilience and promoting sustainable development goals.

## VI Conclusion

This paper proposes a new framework for investigating water-related multi-hazards through leveraging and synthesising existing methods to address the challenges and gaps identified to date. More specifically, building on a comprehensive bibliometric analysis of the multi-hazard literature, the study provides a broad overview and comparison of approaches currently used by the research community to evaluate and model different types of hazard interrelations. This preliminary review, identifying the main gaps in and challenges of current approaches, presents the knowledge base for the design of the novel framework for multi-hazard appraisal able to address geographically specific key considerations, including available and accessible data, community variability and cross-sectoral collaborations.

Future work will involve the utilisation of the framework to investigate natural and anthropogenic controls and drivers of hydrologically induced landslides and flooding at a case-study level. This information will be used to generate regional models and predictions to support the design and implementation of disaster risk reduction and preparedness plans. This progression in our knowledge and understanding can be adapted to cover a broader range of multi-hazard scenarios and a wider geographic perspective.

### Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

### ORCID iD

Julia M Docherty https://orcid.org/0000-0003-3245-3357

### References

Abdulwahid WM and Pradhan B (2017) Landslide vulnerability and risk assessment for multi-hazard scenarios using airborne laser scanning data (LiDAR). *Landslides* 14(3): 1057–1076.

Adhikari P, Hong Y, Douglas KR, et al. (2010) A digitized global flood inventory (1998–2008): Compilation and preliminary results. *Natural Hazards* 55(2): 405–422.

Aksha SK, Juran L and Resler LM (2018) Spatial and temporal analysis of natural hazard mortality in Nepal. *Environmental Hazards* 17(2): 163–179.

Allen SK, Rastner P, Arora M, et al. (2016) Lake outburst and debris flow disaster at Kedarnath, June 2013: Hydrometeorological triggering and topographic predisposition. *Landslides* 13(6): 1479–1491.

Barrantes G (2018) Multi-hazard model for developing countries. *Natural Hazards* 92(2): 1081–1095.

Bathrellos GD, Skilodimou HD, Chousianitis K, et al. (2017) Suitability estimation for urban development using multi-hazard assessment map. *Science of the Total Environment* 575: 119–134.

Beccari B (2016) A comparative analysis of disaster risk, vulnerability and resilience composite indicators. *PLoS Currents* 8.

Berti M, Martina MLV, Franceschini S, et al. (2012) Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. *Journal of Geophysical Research: Earth Surface* 117(F4).

Birkmann J, Cardona OD, Carreño ML, et al. (2013) Framing vulnerability, risk and societal responses: the MOVE framework. *Natural hazards* 67(2): 193–211.

Blaikie P, Cannon TDI, Davis I, et al. (1994) *At Risk: Natural Hazards, People's Vulnerability, and Disasters*. London: Routledge, pp. 21–45.

Buytaert W, Zulkafli Z, Grainger S, et al. (2014) Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science* 2: 26.

Carpignano A, Golia E, Di Mauro C, et al. (2009) A methodological approach for the definition of multi-risk maps at regional level: First application. *Journal of Risk Research* 12(3–4): 513–534.

Carreño ML, Cardona OD and Barbat AH (2007) Urban seismic risk evaluation: a holistic approach. *Natural Hazards* 40(1): 137–172.

Chen HX, Zhang S, Peng M, et al. (2016) A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows. *Engineering Geology* 203: 15–29.

Cutter SL (1996) Vulnerability to environmental hazards. *Progress in Human Geography* 20(4): 529–539.

Cutter SL, Barnes L, Berry M, et al. (2008). A place-based model for understanding community resilience to natural disasters. *Global environmental change* 8(4): 598–606.

Cutter SL, Boruff BJ and Shirley WL (2003) Social vulnerability to environmental hazards. *Social Science Quarterly* 84(2): 242–261.

Dahal RK and Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology* 100(3–4): 429–443.

Dai FC, Lee CF and Ngai YY (2002) Landslide risk assessment and management: An overview. *Engineering Geology* 64(1): 65–87.

Depietri Y and McPhearson T (2018). Changing urban risk: 140 years of climatic hazards in New York City. *Climatic change* 148(1-2): 95–108.

Devkota S, Sudmeier-Rieux K, Penna I, et al. (2014) *Community-based Bio-engineering for Eco-safe Roadsides in Nepal*. Lausanne: University of Lausanne, International Union for Conservation of Nature, Nepal and Department of Soil Conservation and Watershed Management, Government of Nepal.

Duncan JM and Biggs EM (2012) Assessing the accuracy and applied use of satellite-derived precipitation estimates over Nepal. *Applied Geography* 34: 626–638.

Emerton RE, Stephens EM, Pappenberger F, et al. (2016) Continental and global scale flood forecasting systems. *Wiley Interdisciplinary Reviews: Water* 3(3): 391–418.

Galli M, Ardizzone F, Cardinali M, et al. (2008) Comparing landslide inventory maps. *Geomorphology* 94(3–4): 268–289.

Gallina V, Torresan S, Critto A, et al. (2016) A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management* 168: 123–132.

Gao C and Ruan T (2018) Bibliometric analysis of global research progress on coastal flooding 1995–2016. *Chinese Geographical Science* 28(6): 998–1008.

Gautam D (2017) Assessment of social vulnerability to natural hazards in Nepal. *Natural Hazards and Earth System Sciences* 17(12): 2313–2320.

Gautam DK and Dulal K (2013) Determination of threshold runoff for flood early warning in Nepalese Rivers. *IDRiM Journal* 3(1): 126–136.

Gill JC and Malamud BD (2014) Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics* 52(4): 680–722.

Gill JC and Malamud BD (2017) Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. *Earth-Science Reviews* 166: 246–269.

Hannah DM, Demuth S, van Lanen HA, et al. (2011) Large-scale river flow archives: Importance, current status and future needs. *Hydrological Processes* 25(7): 1191–1200.

Hannah DM, Kansakar SR, Gerrard AJ, et al. (2005) Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *Journal of Hydrology* 308(1-4): 18–32.

Haughton G and White I (2018) Risky spaces: Creating, contesting and communicating lines on environmental hazard maps. *Transactions of the Institute of British Geographers* 43(3): 435–448.

Hewitt K and Burton I (1971) *The Hazardousness of a Place: A Regional Ecology of Damaging Events*. Toronto, Canada: University of Toronto Press.

Johnson RM, Edwards E, Gardner JS, et al. (2018) Community vulnerability and resilience in disaster risk reduction: An example from Phojal Nalla, Himachal Pradesh, India. *Regional Environmental Change* 18(7): 2073–2087.

Kansakar SR, Hannah DM, Gerrard J, et al. (2004) Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology: A Journal of the Royal Meteorological Society* 24(13): 1645–1659.

Kappes MS, Keiler M, von Elverfeldt K, et al. (2012) Challenges of analysing multi-hazard risk: A review. *Natural Hazards* 64(2): 1925–1958.

Karpouzoglou T, Dewulf A and Clark J (2016) Advancing adaptive governance of social-ecological systems through theoretical multiplicity. *Environmental Science & Policy* 57: 1–9.

Keating A, Campbell K, Mechler R, et al. (2017) Disaster resilience: What it is and how it can engender a meaningful change in development policy. *Development Policy Review* 35(1): 65–91.

Kirschbaum DB, Adler R, Hong Y, et al. (2012) Advances in landslide nowcasting: Evaluation of a global and regional modeling approach. *Environmental Earth Sciences* 66(6): 1683–1696.

Kirschbaum D, Stanley T and Zhou Y (2015) Spatial and temporal analysis of a global landslide catalog. *Geomorphology* 249: 4–15.

Krakauer N, Pradhanang S, Lakhankar T, et al. (2013) Evaluating satellite products for precipitation estimation in mountain regions: A case study for Nepal. *Remote Sensing* 5(8): 4107–4123.

Krishnan P, Ananthan PS, Purvaja R, et al. (2019) Framework for mapping the drivers of coastal vulnerability and spatial decision making for climate-change adaptation: A case study from Maharashtra, India. *Ambio* 48(2): 192–212.

Kucera P and Steinson M (2017) Development of innovative technology to provide low-cost surface atmospheric observations in data sparse regions. In: *EGU General Assembly Conference Abstracts* (Vol. 19, p. 11639).

Lewis J (1984) A multi-hazard history of Antigua. *Disasters* 8(3): 190–197.

Liu W, Dugar S, McCallum I, et al. (2018) Integrated participatory and collaborative risk mapping for enhancing disaster resilience. *ISPRS International Journal of Geo-Information* 7(2): 68–93.

McCallum I, Liu W, See L, et al. (2016) Technologies to support community flood disaster risk reduction. *International Journal of Disaster Risk Science* 7(2): 198–204.

Mao F, Clark J, Buytaert W, et al. (2018) Water sensor network applications: Time to move beyond the technical? *Hydrological Processes* 32(16): 2612–2615.

Mignan A, Komendantova N, Scolobig A, et al. (2017) Multi-risk assessment and governance. In: Madu CN and Kuei CH (eds) *Handbook of Disaster Risk Reduction and Management*, pp. 357–381.

Mysiak J, Torresan S, Bosello F, et al. (2018) Climate risk index for Italy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376(2121): 20170305.

Papathoma-Köhle M, Kappes M, Keiler M, et al. (2011) Physical vulnerability assessment for alpine hazards: State of the art and future needs. *Natural Hazards* 58(2): 645–680.

Paton D (2008) Risk communication and natural hazard mitigation: How trust influences its effectiveness. *International Journal of Global Environmental Issues* 8(1–2): 2–16.

Paul JD, Buytaert W, Allen S, et al. (2018) Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water* 5(1): e1262.

Pei B, Pang W, Testik FY, et al. (2014) Mapping joint hurricane wind and surge hazards for Charleston, South Carolina. *Natural Hazards* 74(2): 375–403.

Pescaroli G and Alexander D (2018) Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis* 38(11): 2245–2257.

Pescaroli G and Alexander D (2016) Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Natural Hazards* 82(1): 175–192.

Petley DN (2010) On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia. *Quarterly Journal of Engineering Geology and Hydrogeology* 43(4): 487–496.

Petley DN, Hearn GJ, Hart A, et al. (2007) Trends in landslide occurrence in Nepal. *Natural Hazards* 43(1): 23–44.

Prakash S, Mitra AK, Pai DS, et al. (2016) From TRMM to GPM: How well can heavy rainfall be detected from space? *Advances in Water Resources* 88: 1–7.

Preston BL and Stafford-Smith M (2009) *Framing Vulnerability and Adaptive Capacity Assessment: Discussion Paper*. Aspendale: CSIRO Climate Adaptation National Research Flagship.

Reason J (1990) *Human Error*. Cambridge: Cambridge University Press.

Roy J (2001) From data fusion to situation analysis. In: *Proceedings of Fourth International Conference on Information Fusion* (Vol. 2).

Rufat S, Tate E, Burton CG, et al. (2015) Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction* 14(4): 470–486.

Ruiz-Villanueva V, Allen S, Arora M, et al. (2017) Recent catastrophic landslide lake outburst floods in the Himalayan mountain range. *Progress in Physical Geography* 41(1): 3–28.

Shen P, Zhang L, Chen H, et al. (2018) EDDA 2.0: Integrated simulation of debris flow initiation and dynamics considering two initiation mechanisms. *Geoscientific Model Development* 11(7): 2841–2856.

Shrestha MS, Heggen R, Thapa K, et al. (2004) Flood risk and vulnerability mapping using GIS: A Nepal case study. In: *Proceeding of the Second Asia Pacific Association of Hydrology and Water Resources Conference*, (Vol. 1), Singapore, pp. 180–190.

Skilodimou HD, Bathrellos GD, Chousianitis K, et al. (2019) Multi-hazard assessment modeling via multi-criteria analysis and GIS: A case study. *Environmental Earth Sciences* 78(2): 47.

Smith PJ, Brown S and Dugar S (2017) Community-based early warning systems for flood risk mitigation in Nepal. *Natural Hazards and Earth System Sciences* 17(3): 423–437.

Stewart ID (2011) A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology* 31(2): 200–217.

Sudmeier-Rieux K, McAdoo BG, Devkota S, et al. (2019) Invited perspectives: Mountain roads in Nepal at a new crossroads. *Natural Hazards and Earth System Sciences* 19(3): 655–660.

Sullivan-Wiley KA and Short Gianotti AG (2017) Risk perception in a multi-hazard environment. *World Development* 97: 138–152.

Turconi L, Tropeano D, Savio G, et al. (2015) Landscape analysis for multi-hazard prevention in Orco and Soana valleys, Northwest Italy. *Natural Hazards & Earth System Sciences* 15(9): 1963–1972.

UNISDR (2015) *Sendai Framework for Disaster Risk Reduction 2015–2030*. Geneva: UNISDR.

Uprety M, Ochoa-Tocachi BF, Paul JD, et al. (2019) Improving water resources management using participatory monitoring in a remote mountainous region of Nepal. *Journal of Hydrology: Regional Studies* 23: 100604.

Van Eck N and Waltman L (2018) *VOSViewer* version 1.6.9. Leiden University: Centre for Science and Technology Studies of Leiden University.

Van Westen C, Kappes MS, Luna BQ, et al. (2014) Medium-scale multi-hazard risk assessment of gravitational processes. In: Asch TV, Corominas J, Greiving S, et al. (eds) *Mountain Risks: From Prediction to Management and Governance*. Dordrecht: Springer, pp. 201–231.

World Bank (2018) World bank 2018-2019 country classifications. Available at: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups (accessed 6 December 2018).

Xu L, Gober P, Wheater HS, et al. (2018) Reframing socio-hydrological research to include a social science perspective. *Journal of Hydrology* 563: 76–83.

Zogheib C, Ochoa-Tocachi BF, Paul JD, et al. (2018) Exploring a water data, evidence, and governance theory. *Water Security* 4: 19–25.