Climate Change and Human Mobility: An Interdisciplinary Study in the Eastern Hindu Kush

Doctoral Thesis

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Dedicated to my beloved parents, my mother, and in loving memory of my late father.

Abstract

Climate change is significantly impacting the Hindu Kush Himalaya (HKH) region through its adverse effects on the livelihoods of mountain communities. The warming in the region, which exceeds the global average rates, leads to glacier melting, loss of biodiversity, and reduced water resources, posing potential risks to agriculture and water supply in the region. Mountain communities in the Eastern Hindu Kush and the wider HKH region are vulnerable to the changing climate, facing challenges such as changing harvest periods, crop pests, and extreme weather events, which disrupt their lives and livelihoods. In addition, the region's complex environment is prone to a multitude of natural hazards, including floods, landslides, avalanches, earthquakes, droughts, and extreme temperature variations. The impacts of climate change further intensify flood risk, which is a major and recurrent hazard in the region, by altering rainfall patterns and cryospheric changes. The local perceptions of climate change, extreme events, and impacts are not investigated in the Eastern Hindu Kush region. The interconnected hazards require interdisciplinary research to comprehend their complex and interrelated risks to mountain livelihoods.

Against this backdrop, the discourse on climate-induced human migration has transitioned from the initial 'climate refugees' perspective to a more holistic 'climate mobilities' approach which emphasizes that migration decisions are influenced by a variety of factors, including socioeconomic, political, and environmental considerations. Therefore, migration serves as a crucial adaptation strategy in response to evolving conditions, particularly in the resource-dependent mountain communities of HKH.

Nevertheless, there is a significant research gap in understanding the specific dynamics of climate-induced human mobility in this highland region, particularly within the context of Chitral and the Eastern Hindu Kush. This requires further investigation into the complexities of (im)mobilities in this specific region.

This doctoral thesis seeks to investigate the complex relationship between climate change, natural hazards, and human (im)mobility in the Eastern Hindu Kush region, where empirical research is limited. The first aim is to understand the impacts of climate change and natural hazards on mountain livelihoods by exploring local climate change perceptions, the factors shaping them, climate trends, major natural hazards, and abrupt changes in land cover. The second aim then examines the complex interplay between climate change, the environment, and human mobilities, investigating mobility characteristics, the drivers of human mobility and immobility, and the influence of climate change and extreme events on (im)mobility decisions. The third aim emphasizes the development of an interdisciplinary research framework that combines methods from social and physical sciences to study the complex relationship between climate change and human (im)mobility.

This research is conducted at both regional and local levels, though primarily focusing on the Eastern Hindu Kush region and the Lotkuh Valley within the Lower Chitral district of Pakistan. The research methodology for this thesis adopts a mixed methods approach that combines quantitative and qualitative methods. The research involves the analysis of biophysical data collected from satellite datasets, and social data including survey, interviews, and focus groups.

Local perceptions of climate change revealed shifts in temperature, seasonal duration, and precipitation patterns, and these climatic changes significantly affect mountain livelihoods, particularly agriculture and water availability. The comparison of local perceptions with climate data trends provided interesting insights by highlighting areas of convergence, such as increasing annual temperatures, as well as areas of divergence, including variations in precipitation and snow cover trends. Furthermore, the research revealed the impacts of natural extreme events on mountain livelihoods including land cover degradation and forced displacement. This research provides insights into migration patterns, drivers of mobility and immobility, and the influence of environmental and climatic changes on these mobility patterns. The research framework outlined in the thesis combines interdisciplinary methods and offers a comprehensive approach to understanding climate change, natural hazards, and human mobility nexus. Finally, this thesis contributes significantly to the field of climate change and human mobility research in the Eastern Hindu Kush and has the potential for broader application in similar regions.

Zusammenfassung

Der Klimawandel hat erhebliche Auswirkungen auf die Region des Hindukusch-Himalaya (HKH), da er sich negativ auf die Lebensgrundlagen der Berggemeinden auswirkt. Die Erwärmung in der Region, die über dem globalen Durchschnitt liegt, führt zum Abschmelzen der Gletscher, zum Verlust der biologischen Vielfalt und zum Rückgang der Wasserressourcen, was eine potenzielle Gefahr für die Landwirtschaft und die Wasserversorgung in der Region darstellt. Die Berggemeinden am östlichen Hindukusch und in der gesamten HKH-Region sind durch den Klimawandel gefährdet und sehen sich mit Herausforderungen wie wechselnden Erntezeiten, Schädlingsbefall und extremen Wetterereignissen konfrontiert, die ihr Leben und ihre Lebensgrundlage beeinträchtigen. Darüber hinaus ist die komplexe Umwelt der Region anfällig für eine Vielzahl von Naturgefahren, darunter Überschwemmungen, Erdrutsche, Lawinen, Erdbeben, Dürren und extreme Temperaturschwankungen. Die Auswirkungen des Klimawandels verschärfen das Überschwemmungsrisiko, das in der Region eine große und wiederkehrende Gefahr darstellt, durch veränderte Niederschlagsmuster und kryosphärische Veränderungen weiter. Die lokale Wahr- nehmung des Klimawandels, der Extremereignisse und der Auswirkungen ist in der Region des östlichen Hindukusch bisher nicht untersucht worden. Die miteinander verknüpften Gefahren erfordern interdisziplinäre Forschung, um die komplexen und miteinander verbundenen Risiken für die Lebensgrundlagen in den Bergen zu verstehen.

Vor diesem Hintergrund hat sich der Diskurs über die klimabedingte Migration von Menschen von der anfänglichen ”Klimaflüchtlings”-Perspektive zu einem ganzheitlicheren ”Klimamobilitäts”-Ansatz entwickelt, der

betont, dass Migrationsentscheidungen von einer Vielzahl von Faktoren beeinflusst werden, darunter sozioökonomische, politische und ökologische Erwägungen. Daher dient die Migration als entscheidende Anpassungsstrategie als Reaktion auf die sich verändernden Bedingungen, insbesondere in den ressourcenabhängigen Berggemeinden von HKH. Dennoch gibt es eine erhebliche Forschungslücke beim Verständnis der spezifischen Dynamik der klimabedingten menschlichen Mobilität in dieser Hochlandregion, insbesondere im Kontext von Chitral und dem östlichen Hindukusch. Dies erfordert eine weitere Untersuchung der Komplexität von (Im-)Mobilitäten in dieser spezifischen Region.

In dieser Dissertation soll die komplexe Beziehung zwischen Klimawandel, Naturgefahren und menschlicher (Im-)Mobilität in der östlichen Hindukusch-Region untersucht werden, wo es bisher noch kaum empirische Untersuchungen gibt. Das erste Ziel besteht darin, die Auswirkungen des Klimawandels und der Naturgefahren auf die Lebensgrundlagen in den Bergen zu verstehen, indem die Wahrnehmung des Klimawandels vor Ort, die Faktoren, die diese beeinflussen, die Klimatrends, die wichtigsten Naturgefahren und die abrupten Veränderungen der Bodenbedeckung untersucht werden. Das zweite Ziel befasst sich dann mit dem komplexen Zusammenspiel zwischen Klimawandel, Umwelt und menschlicher Mobilität, wobei Mobilitätsmerkmale, die Triebkräfte menschlicher Mobilität und Immobilität sowie der Einfluss von Klimawandel und Extremereignissen auf (Im-)Mobilitätsentscheidungen untersucht werden. Das dritte Ziel fokusiert sich auf die Entwicklung eines interdisziplinären Forschungsrahmens, der Methoden aus den Sozial- und Naturwissenschaften kombiniert, um die komplexe Beziehung zwischen Klimawandel und menschlicher (Im-)Mobilität zu untersuchen.

Diese Forschung wird sowohl auf regionaler als auch auf lokaler Ebene durchgeführt, wobei der Schwerpunkt auf der östlichen Hindukusch-Region und dem Lotkuh-Tal im Bezirk Lower Chitral in Pakistan liegt. Die Forschungsmethodik für diese Arbeit beruht auf einem gemischten Ansatz, der quantitative und qualitative Methoden kombiniert. Die Forschung umfasst die Analyse biophysikalischer Daten, die anhand von Satellitendatensätzen erhoben wurden, sowie sozialer Daten, darunter Erhebungen, Interviews und Fokusgruppen.

Die lokale Wahrnehmung des Klimawandels zeigt Verschiebungen bei den Temperaturen, der Dauer der Jahreszeiten und den Niederschlagsmustern. Diese klimatischen Veränderungen haben erhebliche Auswirkungen auf die Lebensgrundlagen im Bergland, insbesondere auf die Landwirtschaft und die Verfügbarkeit von Wasser. Der Vergleich der lokalen Wahrnehmu- ngen mit den Trends der Klimadaten lieferte interessante Einblicke, indem er Bereiche der Konvergenz, wie z. B. steigende Jahrestemperaturen, sowie Bereiche der Divergenz, wie z. B. Schwankungen bei den Niederschlags- und Schneedeckentrends, aufzeigte. Darüber hinaus zeigte die Untersuchung die Auswirkungen von Extremereignissen auf die Lebensgrundlagen in den Bergen, einschließlich der Verschlechterung der Bodenbedeckung und Zwangsumsiedlungen. Die Forschungsarbeit bietet damit Einblicke in die Migrationsmuster, die Triebkräfte für Mobilität und Immobilität sowie den Einfluss von Umwelt- und Klimaveränderungen auf diese Mobilitätsmuster. Der in dieser Arbeit skizzierte Forschungsrahmen kombiniert interdisziplinäre Methoden und bietet einen umfassenden Ansatz zum Verständnis des Zusammenhangs zwischen Klimawandel, Naturgefahren und menschlicher Mobilität. Schließlich leistet diese Arbeit einen wichtigen Beitrag zur Erforschung des Klimawandels und der menschlichen Mobilität am östlichen Hindukusch und hat das Potenzial für eine breitere Anwendung in ähnlichen Regionen.

خلاصہ

پہاڑی آبادیوں کے ذریعہ معاش پر موسمی تبدیلی کے منفی اثرات، ہندوکش ہمالیہ (HKH) کے خطے پر اس موسمی تبدیلی کے نمایاں اثر کی عکاسی کرتے ہیں۔ اس خطے میں عالمی اوسط سے بھی زیادہ بڑھتی ہوئی گرمی برفانی تودوں کے پگھلنے، حیاتیاتی تنوع کے نقصان، اور پانی کے وسائل میں کمی کا باعث بن رہی ہے جسکی وجہ سے خطے میں زراعت اور پانی کی فراہمی کو ممکنہ خطرات لاحق ہیں۔ ہندوکش اور بالخصوص مشرقی ہندوکش میں بسنے والی پہاڑی آبادیوں کو موسمیاتی تبدیلیوں کے زیرِ اثر ہوتے ہوئے کئی چیلنجز کا سامنا ہے جن میں فصلوں کے پکنے اور کٹائی میں تبدیلی، فصلی کیڑے اور شدید موسمی واقعات قابلِ ذکر ہیں جو کہ لوگوں کی زندگیوں اور ذریعہ معاش میں بگاڑ کا باعث بنتے ہیں۔ اسکے علاوٰہ خطے کا پیچیدہ ماحول اسے کئی قدرتی خطرات بشمول سیلاب، زمین کا سرکنا اور کٹاو، برفانی تودوں کا سرکنا، زلزلے، خشک سالی اور درجہ حرارت کے شدید تغیر سے دوچار کرتا ہے۔ موسمیاتی تبدیلی کے اثرات کی وجہ سے سیلاب جو کہ خطے میں متواتر رونما ہونے والا بڑا خطرہ ہے بارش کے بدلتے ہوئے پیٹرن اور کریوسفیرک تبدیلیوں کی وجہ سے مذید شدت اختیار کرلیتا ہے. مشرقی ہندوکش کے خطے میں موسمیاتی تبدیلی، شدید واقعات اور ان کے اثرات سے منسلک مقامی تصورات کا مطالعہ نہیں کیا جاتا۔ پہاڑی علاقوں کے ذریعہ معاش سے جڑے پیچیدہ خطرات کے باہمی تعلق کو سمجھنے کے لیے باہم منسلک خطرات پر بین الضابطہ ریسرچ کرنے کی ضرورت ہے۔

اس تناظر میں موسمیاتی تبدیلی کی وجہ سے ہونے والی انسانی ہجرت سے جڑی گفتگو ابتدائی اصطلاح ""موسمیاتی پناہ گزین"" سے ایک جامع اصطلاح ""موسمیاتی نقل و حرکت"" کی طرف منتقل ہو چکی ہے یہ جامع اصطلاح ان مختلف عوامل کا احاطہ کرتی ہے جو ہجرت کرنے کے فیصلوں پر اثرانداز ہوتے ہیں جیسا کہ معاشی، معاشرتی، سیاسی اور موسمیاتی عوامل۔ لہذا، پہاڑی علاقوں میں بدلتی ہوئی صورتحال میں لوگوں کی ہجرت ایک اہم حکمتِ عملی کے طور پر کام کرتی ہے خاص کر کوہ ہندوکش کی پہاڑی آبادیوں کے لیے جن کا کلِ انحصار وسائل پر ہوتا ہے۔ اس کے باوجود، اس پہاڑی خطہ میں، خاص طور پر چترال اور مشرقی ہندوکش کے مخصوص پس منظر میں، موسمیاتی تبدیلی کی وجہ سے انسانی نقل و حرکت کو سمجھنے میں ایک اہم تحقیقی خلا موجود ہے۔ اس کے لیے اس مخصوص خطے میں نقل و حرکت کی پیچیدگیوں پر مزید تحقیق کی ضرورت ہے۔

ڈاکٹریٹ کا یہ مقالہ مشرقی ہندوکش کے علاقے میں موسمیاتی تبدیلیوں، قدرتی خطرات اور انسانی نقل و حرکت کے درمیان پیچیدہ تعلق کے بارے کھوج کا متلاشی ہے، جہاں تجرباتی تحقیق محدود ہے۔ پہلا مقصد موسمیاتی تبدیلی سے منسلک مقامی تصورات، ان تصورات کو تشکیل دینے والے عوامل، موسمیاتی رجحانات، اہم قدرتی خطرات اور

سطح زمین پر رونما ہونے والی اچانک تبدیلیوں کو دریافت کرتے ہوئے یہ سمجھنا ہے کہ موسمیاتی تبدیلی اور قدرتی خطرات کے پہاڑی آبادیوں کے ذریعہ معاش پر کیا اثرات ہیں۔ دوسرا مقصد موسمیاتی تبدیلیوں، ماحولیات اور انسانی نقل و حرکت کے درمیان پیچیدہ تعامل، نقل و حرکت کی خصوصیات کی تحقیقات، انسانی نقل و حرکت اور عدم استحکام کے محرکات، اور نقل و حرکت کے فیصلوں پر موسمیاتی تبدیلیوں اور شدید واقعات کے اثر ورسوخ کا مطالعہ کرنا ہے۔ تیسرا مقصد ایک بین الضابطہ تحقیقی فریم ورک کی تشکیل پر زور دینا ہے جو موسمیاتی تبدیلی اور انسانی نقل و حرکت کے درمیان پیچیدہ تعلق کا مطالعہ کرنے کے لیے سماجی اور طبعی علوم کے طریقوں کو یکجا کرنا ہے۔

یہ تحقیق علاقائی اور مقامی دونوں سطحوں پر کی گئی ہے، تاہم بنیادی طور پر توجہ مشرقی ہندوکش اور پاکستان میں چترال ڈسٹرکٹ میں واقع لوٹکوہ وادی پر مرکوز ہے۔ تحقیق کے لیے مخلوط طریقہ کار اپنایا گیا ہے جس میں کوانٹیٹیٹو اور کوالیٹیٹو تحقیقی طریقہ کار کا امتزاج شامل ہے۔ اس تحقیق میں سیٹلائٹ ڈیٹا سیٹس سے جمع کیے گئے بائیو فزیکل ڈیٹا اور سروے، انٹرویوز اور فوکس گروپس سمیت سماجی ڈیٹا کا تجزیہ شامل ہے۔

موسمیاتی تبدیلیوں کے مقامی تصورات نے درجہ حرارت، موسم کے دورانیے اور بارشوں کے پیٹرنز میں تبدیلی کو ظاہر کیا اور یہ وہ تبدیلیاں ہیں جو پہاڑی آبادیوں کے ذریعہ معاش خاص کر کے زراعت اور پانی کی فراہمی پر اثرانداز ہوتی ہیں۔ موسمیاتی اعداد و شمار کے رجحانات کے ساتھ مقامی تصورات کے موازنے نے کنور جنس کا احاطہ کیا جیسا کہ سالانہ درجہ حرارت میں اضافہ، اسکے ساتھ ساتھ ڈائیور جنس کا بھی احاطہ کیا جیسا کہ بارش اور برف باری کے رجحانات میں تبدیلیاں۔ مزید برآں، تحقیق نے پہاڑی آبادیوں کے ذریعہ معاش پر قدرتی شدید واقعات کے اثرات کو ظاہر کیا ہے جن میں زمین کے احاطہ میں کمی اور جبری نقل مکانی شامل ہے۔ یہ تحقیق ہجرت کے پیٹرنز، نقل و حرکت اور عدم نقل و حرکت کے پس پردہ عوامل اور ان نقل و حرکت کے پیٹرنز پر ماحولیات اور موسمیاتی تبدیلی کے اثرات کے بارے معلومات فراہم کرتی ہے۔ مقالے میں بیان کردہ تحقیقی فریم ورک بین الضابطہ طریقوں کو یکجا کرتا ہے اور موسمیاتی تبدیلی، قدرتی خطرات اور انسانی نقل و حرکت کے گٹھ جوڑ کو سمجھنے کے لیے ایک جامع نقطہ نظر پیش کرتا ہے۔ آخیر اً یہ مقالہ مشرقی ہندوکش میں موسمیاتی تبدیلی اور انسانی نقل و حرکت کی تحقیق کے میدان میں اہم کردار ادا کرتا ہے اور اسی طرح کے خطوں میں وسیع تر اطلاق کی صلاحیت رکھتا ہے۔

Preface

This thesis doctoral thesis is the culmination of extensive research that delves into the complex nexus between climate change and human mobility in the Eastern Hindu Kush. Mountain communities inhibiting this region face profound challenges as climate change and natural hazards disrupt their traditional livelihoods. Despite this, the Eastern Hindu Kush has received less scholarly attention compared to other regions in the Hindu Kush Himalaya, primarily due to its remote and inaccessible location.

The complexities of the region's geography, coupled with limited climate data stations, pose significant challenges when analyzing local climate trends. Equally important is understanding the perceptions of climate change, identifying extreme events, and understanding their diverse impacts on human mobility and immobility in the area. Such insights are critical for formulating effective adaptation and resilience strategies for mountain communities.

This research was conducted to explore the interconnections between climate change, natural hazards, and human mobility in the Eastern Hindu Kush. The multifaceted dimensions encompassing the physical climate, natural environment, human perceptions, impacts, and mobility outcomes required an interdisciplinary approach. This study draws on methods from both human and physical geography to present a comprehensive examination of the topic. The study offers insights into climate change impacts on mountain livelihoods and their interrelations with human mobility in the region.

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List of Acronyms

AKDN	Aga Khan Development Network
BFAST	Breaks For Additive Seasonal and Trend
GLOF	Glacial Lake Outburst Flood
HKH	Hindu Kush Himalaya
IPCC	Intergovernmental Panel on Climate Change
MODIS	Moderate Resolution Imaging Spectroradiometer
MSAVI	Modified Soil Adjusted Vegetation Index
NDVI	Normalized Difference Vegetation Index
NELM	New Economics of Labor Migration
NGO	Non-governmental organization
USGS	United States Geological Survey

RESEARCH DESIGN

1. Motivation and Outline

”They [my two brothers] have migrated to increase their income … giving money to parents, children’s expenses, all these responsibilities must be borne … I migrated for education and the brothers … These are the reasons but it is not the one [reason] … in 2016, there was a big disaster that struck here in which nine lives were lost, in the avalanche. So because of this, some people moved; some in the village to another place, some outside the village. But there are different factors in it. [There is] no single factor.”

Taj Muhammad, Shershal village in the Lotkuh valley, Pakistan, June 2020

Mountain communities are facing the adverse impacts of climate change on their livelihoods in the Hindu Kush Himalaya (HKH) region. Rising temperatures are leading to glacier melting, biodiversity loss, and a decrease in water resources, endangering the livelihoods of millions of people living in the highlands and lowlands. Furthermore, the region’s complex natural environment is highly susceptible to various natural hazards and associated extreme events. The impact of climate change exacerbates the occurrence of intense and frequent extreme events, which disrupt mountain livelihoods and the local environment significantly. Among these, flooding, one of the most devastating and recurrent hazards, is influenced by climate-induced changes in the cryosphere and hydrological patterns of the region. Extreme events are also causing changes in the land cover through degradation, erosion, and depletion of scarce land resources. Analysis of climate trends at the local level is challenging due to the complex geography of the region and the sparse distribution of climate data stations. Moreover, understanding the perceptions of climate change, identifying extreme events, and exploring their diverse impacts on local livelihoods, including changes in land cover, are crucial for developing effective adaptation and resilience strategies in mountain communities.

As climate change scholarship gains momentum, the nexus between climate change and human mobility is receiving global attention. In this context, adopting a mobilities perspective is essential for unraveling the intricate relationship between climate change, the natural environment, and human mobility. The mountain communities whose livelihoods heavily rely on natural resources, are under immense stress due to the interplay of climate change and natural hazards in the HKH region. Human migration has always existed and serves as an adaptation strategy to cope with scare resources and livelihood opportunities in the mountain regions. However, with the increasing impact of alterations in climatic conditions and a multitude of extreme events on mountain livelihoods, migration is becoming increasingly important as an adaptation strategy. Therefore, the latest research is imperative to understand current mobility patterns, including the drivers and their interrelationships with climate change and extreme events in the HKH region.

In this context, this research was conducted to explore the nexus between climate change, natural hazards, and human mobility in the Eastern Hindu Kush. The choice of this region was primarily motivated by its distinctive geographical challenges, including its remote and inaccessible nature, as well as the limited body of scholarship available on the subject of this thesis. Given the multifaceted dimensions encompassing the physical climate and natural environment, as well as human dimensions, including perceptions, impacts, and mobility outcomes, this research is inherently interdisciplinary and draws on methods and approaches from both human and physical geography. This cumulative dissertation comprises three distinct parts, briefly outlined as follows:

Research Design

This section sets the stage for the cumulative thesis by providing background information on climate change, natural hazards, and human (im)mobilities. It explores the relevant literature and identifies research gaps (Chapter 2). While it primarily draws from the existing scholarship in the HKH region, it also considers insights from other regions. Furthermore, this part offers a summary of the debate on the relationship between climate change and human mobility, building on the theoretical and empirical literature in the field. Chapter 3 outlines the research aims and presents corresponding questions.

Chapter 3 provides an overview of the geographical areas where this research was conducted. Finally, the methodological approach, encompassing various datasets used in this research, as well as data collection and analysis procedures, are summarized in Chapter 4.

Publications

The central portion of this cumulative thesis comprises four publications produced during the course of this doctoral project (Chapters 6, 7, 8 & 9). This part offers each scientific manuscript, including an overview, publication status, and the individual contributions of the author.

Synthesis

The final section of the thesis builds on the publications generated in this research. It provides a comprehensive discussion of significant research findings in the context of the research aims and questions (Chapter 10). Moreover, it addresses the implications and limitations of this research study. This thesis concludes with an outlook, suggesting directions for future research (Chapter 11).

2. Introduction

2.1 Climate Change in the Hindu Kush Himalaya

The mountain region of Hindukush, Karakoram, and Himalaya (HKH) is an important geo-ecological region that has the origins of 10 major river basins (E. Sharma et al., 2019). The region also called the Third Pole, has the largest permanent concentration of snow and ice outside polar regions and supplies water to almost 2 billion people (Yao et al., 2022).

HKH supports the livelihoods of millions of people inhibiting both its highlands and lowlands by offering important ecosystem services that include water, energy, and food (E. Sharma et al., 2019). However, the region is grappling with the impacts of climate change, which are causing significant alterations in its cryospheric and hydrological regimes (You et al., 2017). The rate of warming in HKH consistently exceeds the global average, posing substantial challenges (Arias et al., 2021; Kraaijenbrink et al., 2017). Further projections indicate that even if global warming is limited to 1.5 °C, the HKH region is expected to experience warming higher than the global average by at least 0.3 °C, with specific hotspots like the northwest Himalaya and Karakoram regions facing a 0.7 °C rise in temperature (Raghavan Krishnan et al., 2019).

Over the past century, the HKH region has witnessed a rising trend in temperature and a declining trend in precipitation (Ren et al., 2017). Temperature extremes have increased, while cold extremes have decreased (Arias et al., 2021). This temperature shift is not only noticeable but also concerning, with the region experiencing an uptick in the frequency and intensity of temperature-based indices, indicating a trend toward more extreme values in the region (Raghavan Krishnan et al., 2019).

The substantial warming of the region carries significant consequences, including the accelerated melting of glaciers, loss of biodiversity, and diminished water resources (Kraaijenbrink et al., 2017; Raghavan Krishnan et al., 2019; Nie et al., 2021). With global warming, the snow cover and the glaciers in HKH are thinning and retreating with the exception of the Karakoram and eastern Pamirs (Arias et al., 2021; Bolch et al., 2019; Hewitt, 2005, 2011). The accelerated loss of glacier mass may contribute to increased meltwater, especially in the warmer seasons (You et al., 2017). Moreover, global warming is likely to exacerbate water scarcity in the Indus and Amu Darya basins (Yao et al., 2022). This has profound implications for millions of people who rely on these rivers for agriculture, hydropower generation, and domestic use (Raghavan Krishnan et al., 2019). Moreover, the Intergovernmental Panel on Climate Change (IPCC) Report finds that snow and glacier cover will continue to decrease in most parts of the HKH region in the 21st century (Arias et al., 2021).

The persistent trend of glacier melting has direct implications for the magnitude and timing of glacial run-off, with significant consequences for irrigation in arid regions reliant on glacial melt (Bolch et al., 2019). Furthermore, the melting of glaciers and warming are contributing to the increase in the number of glacial lakes and their rapid expansion in the HKH region (Wang et al., 2015). Recent assessments reveal an increase in the number of glacial lakes over the past decade, with accelerated growth at elevations higher than 4400 m, above sea level (F. Chen et al., 2021). These lakes are integral to the region's hydrology but also pose potential risks to the local environment and settlements (Schmidt et al., 2020). The surge in the glacial meltwater elevates the risk of glacial lake outburst floods (GLOFs), which subsequently jeopardize water availability during dry seasons (Ives et al., 2010; Shugar et al., 2020).

Mountain livelihoods, particularly those rooted in crop-livestock agriculture, are highly dependent on fragile ecosystem services (N. Wu et al., 2014). However, these mountain regions are grappling with a gradual decline in their natural resource base, driven by factors like population growth, rapid urbanization, over-grazing, soil erosion, and deforestation (Gioli et al., 2019; Hewitt & Mehta, 2012; Wester et al., 2019a). The vulnerability of mountain livelihoods is further compounded by their distinct characteristics, characterized by socioeconomic marginalization, inaccessibility, and fragility (Gioli et al., 2019).

Weather and climate shifts have a significant impact on mountain livelihoods. The HKH region has witnessed shifts in weather patterns due to climate change, including rising temperatures and altered precipitation patterns (Raghavan Krishnan et al., 2019; Treydte et al., 2006). These changes lead to delayed harvests, crop pests, and diminished agricultural yields (Ajani & van der Geest, 2021; A. Hussain et al., 2016; Vogel et al., 2019). In addition to climate change, natural hazards pose a significant threat to the lives and livelihoods of mountain communities. Extreme events triggered by these hazards often result in human displacement, degradation of agricultural land, destruction of crops, and disruptions to irrigation systems, housing, and infrastructure (Ajani & van der Geest, 2021; A. Hussain et al., 2016). The frequency and intensity of extreme weather events such as droughts, floods, and storms have increased.

On the one hand, it is important to study the perceptions of the local people to understand climate change and its impacts at the societal level and guide adaptation and risk reduction measures. The existing literature suggests that perceptions of climate change are multifaceted and influenced by various factors, including personal experiences with climate change, age, gender, education, and political orientation, among others (Lujala et al., 2015; Poortinga et al., 2019; Sloggy et al., 2021; Weber, 2016; Xie et al., 2022). Moreover, several studies explored the local perceptions of climate change and its impacts, with a particular focus on natural hazards such as floods in the HKH region (Ajani & van der Geest, 2021; R. R. Banerjee, 2015; S. Banerjee et al., 2011; Bhatta et al., 2019; Dilshad et al., 2019; A. Hussain et al., 2016; Joshi et al., 2013). These studies have collectively revealed that the local populations in the wider HKH region perceive climate change and its associated impacts on their livelihoods.

On the other hand, analysis of climate trends is crucial to understand long-term climate patterns and to assess vulnerabilities and risks. Numerous studies have examined climate variables such as snowfall, precipitation, and temperature trends in the HKH region (Ren et al., 2017; Sun et al., 2017). However, most of these earlier investigations relied on climate data from meteorological stations, which are sparse in the HKH and often carry uncertainties due to the region's varying altitudes and microclimates (Dahri et al., 2021; S. P. Singh et al., 2011; Spies, 2020). To address these challenges, researchers have turned to gridded products, notably the 5th generation European Centre for Medium-Range Weather Forecasts ECMWF Re-Analysis (ERA5), as more reliable sources for climate data (Dahri et al., 2021; Z. Syed et al., 2022). However, remote sensing-based techniques need to be adapted to suit the complexities of the region (Winiger et al., 2005).

Recent research studies in the HKH region have sought to bridge the gap between perceptions of climate change and hydrometeorological analyses of climate data. However, studies that successfully integrate both perceptions and climate trend analyses remain relatively scarce in the HKH region, especially the Eastern Hindu Kush. Some notable exceptions include research conducted in India, Nepal, and the Nagar District in the Gilgit-Baltistan region of Pakistan, which compared local perceptions with climate data from meteorological stations (Macchi et al., 2015; Pandey et al., 2019; R. K. Sharma & Shrestha, 2016). Similar integrated studies have been undertaken in various other regions, such as northern Ghana (Guodaar et al., 2021), the Qilian Mountains in northwest China (Xie et al., 2022), the Pamir Mountains of Tajikistan (Haag et al., 2021), and the Punjab Province of Pakistan (Abid et al., 2019), among others.

Notwithstanding these previous studies, there remains a research gap in the Eastern Hindu Kush region when it comes to exploring climate change perceptions and their integration with climate trend analysis. Additionally, there is a crucial research gap in the literature regarding the integration process itself, which often necessitates an interdisciplinary approach that combines different research methods. The need for more comprehensive research that effectively merges climate change perceptions with robust climate trend analyses remains an area open for further exploration in the HKH region and beyond.

2.2 Multi-Hazards and Impacts

The HKH region has a fragile and complex environmental landscape that is highly susceptible to a multitude of multi-hazards (Hewitt, 1992; Rusk et al., 2022; Vaidya et al., 2019b). These multi-hazards, also referred to as connecting hazards or connected extreme events, signify the concurrent occurrence of multiple natural hazards in specific communities or locations (Drakes & Tate, 2022). These events are further shaped by their interplay with both physical and social drivers (Drakes & Tate, 2022; Raymond et al., 2020).

In the HKH region, the interplay of high mountains, glaciers, deep valleys, heightened seismic activity, diverse climatic conditions, and extensive river systems creates a dynamic and multifaceted environment where multiple hazards can occur simultaneously or in rapid succession (Vaidya et al., 2019b; Wester et al., 2019a). The region faces a range of widespread hazards, including floods, landslides, earthquakes, avalanches, droughts, and extreme temperature variations (Rusk et al., 2022). Among these, floods, and landslides stand out as the most recurrent and disruptive hazards. These events are often triggered by intense monsoon precipitation, and increased warming and result in cascading and interconnected effects, posing significant challenges to the region's socioeconomic development and sustainability (Arias et al., 2021).

Floods in the HKH region are characterized by heavy rainfall, rapid snowmelt, and overflowing rivers and streams in summer. Both riverine and flash floods are the most common hazards in the region with a higher impact on people's lives and livelihoods (S. S. Shah et al., 2023). These hazards account for 17% of fatalities and are responsible for 51% of the damage in the region (Vaidya et al., 2019b). The complex topography, featuring steep slopes and narrow valleys, accelerates the flow of water during intense rainfall, increasing the risk of land erosion, landslides, and debris deposition in the farmlands (Rusk et al., 2022; Shaw & Nibanupudi, 2015). Flood risks are particularly heightened during the monsoon seasons (Vaidya et al., 2019b), extending from June to September, and can also occur in the spring when glacial melting coincides with heavy rainfall. Flash floods, often concentrated in short durations of intense rainfall, or the breaching of dams and glacial lakes by avalanches or landslides (Harrison et al., 2018; Lu et al., 2022; Sati, 2022), add to the unpredictability and severity of risks to local communities (S. H. Shah, 2015; G. Singh & Pandey, 2021). Furthermore, the region has an increased risk of GLOF events, and several instances of GLOF-triggered floods reported in Chitral in the Eastern Hindu Kush and the region (Ashraf et al., 2021b; Ashraf et al., 2012; Vaidya et al., 2019b; Veh et al., 2018).

Climate change exacerbates flood risk by altering the intensity and variability of rainfall patterns and accelerating changes in the cryosphere (Ashraf et al., 2014). Glacial retreat, the rapid melting of snow cover, and the formation of glacial lakes are consequences of rising temperatures (Ding et al., 2021). Unsustainable land use practices, such as deforestation and poorly planned urbanization, further disrupt the hydrological cycle, increase runoff, and alter water flow patterns, ultimately increasing the flood risk (Atta-ur-Rahman & Khan, 2011, 2013; Shaw & Nibanupudi, 2015).

Landslides are another recurring natural hazard in the HKH region. The area's rugged topography with more than 40% of the land area having a slope of 15° or more, intense precipitation coupled with active tectonic activity, make it a global hotspot of landslide risk (Vaidya et al., 2019b). The hydroclimatic conditions and fragile geological characteristics of the region make it susceptible to landslides (G. Rahman et al., 2022; Yang et al., 2020). The landslides are further triggered by frequent earthquakes in the region (Niyazov & Nurtaev, 2013), or hydroclimatic conditions. Anthropogenic activities such as deforestation, improper land development, construction on the slopes, and undercutting for infrastructure development increase people's vulnerability to landslides (G. Rahman et al., 2019; Vaidya et al., 2019b). In addition, avalanches are a common hazard during the winter season in the HKH region (Ballesteros-Cánovas et al., 2018; Rusk et al., 2022), and can also be triggered by earthquakes and unsustainable land use practices, further increasing the vulnerability of the local population (Vaidya et al., 2019b).

The arid and semi-arid areas in HKH face the threat of drought or drought-like conditions. Changes in climate patterns, including precipitation and rising temperatures, contribute to drought conditions (Raghavan Krishnan et al., 2019) and water scarcity (Z. Ahmad et al., 2020; Scott et al., 2019). Since the region heavily relies on meltwater from snow cover and glaciers, climate change can disrupt water availability and create drought conditions by altering snow accumulation, glacier retreat, and hydrological regimes that all have implications for the local populations (Nüsser, 2017; Nüsser et al., 2019; Pritchard, 2019). Furthermore, extreme temperature-related hazards, such as heatwaves, coldwaves, and extreme winter conditions, affect various areas in HKH (Rusk et al., 2022). Heatwaves, in particular, are expected to increase in frequency, duration, and intensity in the region (Vaidya et al., 2019b).

Natural hazards and associated extreme events are rising in terms of their frequency, the number of people impacted, and economic losses in the HKH region (Vaidya et al., 2019b). This rise is attributed to several factors including environmental degradation and climate change (Vaidya et al., 2019b). The occurrence of compound events resulting from multiple hazards causes severe socioeconomic impacts (Ridder et al., 2020). The compound events are triggered by different combinations of hazards and are driven by both physical and societal drivers (Raymond et al., 2020). The connected events such as floods, landslides, and avalanches, often lead to severe consequences that significantly impact local livelihoods and result in household food insecurity (A. Hussain et al., 2016; Rusk et al., 2022). Furthermore, the impacts of extreme events and climate change also influence human mobility (including forced displacement, migration, and immobility), discussed in the next section.

Despite significant research in the HKH region, a critical research gap remains regarding the comprehensive understanding of multi-hazards and the interconnected impacts of these multi-hazards on local communities and their livelihoods. The Eastern Hindu Kush region received very limited attention in the scholarship on the hazards and their societal impacts. Particularly, there is a need to investigate the abrupt changes in land cover resulting from extreme events and land use practices, in addition to understanding the impact of hazards on livelihoods in this region. This interdisciplinary research is essential for developing effective strategies to mitigate the complex and interconnected risks faced by vulnerable mountain communities (Karki et al., 2011).

2.3 Climate Change, Environment, and Human Mobility

With the increasing focus on climate change and its impacts on the global south, the discourse on climate or environment-induced migration gained momentum (Piguet, 2010, 2022). The debate on climate change, the environment, and human migration has seen a shift in narratives. The earlier view advocated that climate change and global warming will cause mass migration of "climate refugees" (Biermann & Boas, 2010; Myers, 2002). The advocates of such claims relied on modeling studies that predicted millions of such climate refugees. This view also termed "alarmist", is linked mass exodus of migrations from developing countries to developed countries with implications for global security and stability and is dominating the climate change-security agenda. The critics of the alarmist view argue that this view oversimplifies the link between climate change and migration (Doevenspeck, 2011; Wiegel et al., 2019). Furthermore, it is argued that the estimates of "climate refugees" or "mass migration" are deterministic and largely neglect the broader socioeconomic, cultural, and political drivers (Black, Adger, et al., 2011; Romankiewicz & Doevenspeck, 2015).

The currently predominant perspective argues that the relationship between climate change, environment, and human migration is complex (Black, Adger, et al., 2011; R. A. McLeman & Gemenne, 2018; Milan et al., 2015). This led to the rise of the 'migration as adaptation' discourse (Black, Adger, et al., 2011; Black, Bennett, et al., 2011; Wiegel et al., 2019). The migration process itself is embedded in an economic, political, cultural, environmental, and social context that is continuously changing (Afifi, 2011; Boas et al., 2019; Groth et al., 2020; Hunter & Simon, 2022; R. McLeman, 2018; Romankiewicz et al., 2016; Wiegel et al., 2019). Therefore, it is influenced by individual choices, adaptive capacity, and the broader socioeconomic, cultural, and political context (Black, Bennett, et al., 2011; Wiegel et al., 2019). Moreover, migration is seen as an important adaptation strategy to changes in the socioeconomic, political, and natural environment (Groth et al., 2020; Hunter & Simon, 2022; R. A. McLeman & Gemenne, 2018; Romankiewicz et al., 2016). Environmental factors are just one of many drivers impacting migration decisions (Kaczan & Orgill-Meyer, 2020; Morales-Muñoz et al., 2020). However, scholars also argue that environmental change will increase migration through its interplay with social, economic, political, demographic, and environmental drivers of migration (Black, Adger, et al., 2011; Milan et al., 2015). For instance, agricultural land is eroded by floods and landslides, thus undermining the agriculture base of a community, and forcing them to migrate. In certain circumstances, environmental change can erode productive assets such as crops and livestock thus acting as a barrier to migration (Black, Adger, et al., 2011).

Migration has temporal (seasonal, temporary non-seasonal, recurrent, continuous, and permanent) and spatial (intra-urban, internal, and international) dimensions (R. A. McLeman, 2014; R. A. McLeman & Gemenne, 2018). Overall, migration decision-making is a product of several events and conditions and may generate opportunities as well as risks for a migrant (Black, Adger, et al., 2011; R. A. McLeman, 2014). It is argued that migration decision-making depends on individual and household characteristics and happens mainly due to the availability of economic capital to migrate to other areas (Government Office for Science, 2011). Research suggests that migration because of environmental change and extreme weather events can be an adaptation strategy that enables a household or community to diversify its livelihoods by choosing labor migration, as well as a failure to adapt to changing environmental conditions (S. Banerjee et al., 2011; Gioli, Khan, Bisht, & Scheffran, 2014; Gioli et al., 2019; Milan et al., 2015). Households adopt migration as a strategy to diversify their income and reduce any losses to potential risk by sending young adults to places of higher income (Gioli et al., 2019). Moreover, the populations who do not have the necessary resources (capital, assets, etc.) to migrate will be ‘trapped’ in hazard-prone areas or forced to migrate, thus facing increasing vulnerability and exposure to environmental hazards (Adger et al., 2015; Zickgraf, 2018, 2021b).

In the recent discourse concerning the complex relationship between climate change and human migration, there has been a notable transition from the concept of ’climate or environmental migration’ to a more comprehensive framework known as ’climate mobilities’ (Boas et al., 2019; Boas et al., 2022; Cundill et al., 2021). This evolving perspective encourages a more holistic comprehension of the intricate interplay between human mobility and climate change, acknowledging the vast spectrum of movements that are deeply entrenched in local historical, structural, and political contexts (Boas et al., 2022; Wiegel et al., 2019).

The concept of ’climate mobilities’ posits that the dynamics of human movement in the context of climate change can manifest in diverse forms, encompassing not only conventional long-distance migration but also short-distance forced displacement, rural-to-urban migration, and even the immobility of individuals who, for various reasons, cannot or choose not to relocate from areas exposed to climate risks (Boas et al., 2022). This perspective acknowledges the multifaceted nature of human mobility and underscores that it extends beyond the binary notions of migration and non-migration in the context of climate-induced environmental changes (Boas et al., 2019; Wiegel et al., 2019). Moreover, the concept of ’climate mobilities’ is rooted in the broader framework of the ’mobilities paradigm’ (Sheller & Urry, 2006), which examines the role that various forms of movement play in shaping social institutions and practices. It goes further by exploring the intricate combinations of these diverse mobilities, recognizing that human movement is deeply intertwined with the fabric of contemporary societies and extends far beyond traditional notions of migration (Sheller & Urry, 2016). This paradigm shift is instrumental in facilitating a nuanced understanding of the multifaceted and evolving nature of human responses to climate change and the intricate ways in which mobility, immobility, and various hybrid forms of movement shape contemporary human experiences in the face of environmental transformations (Sheller & Urry, 2016).

As noted in the previous sections, climate change has significant implications for the mountain areas of the Eastern Hindu Kush, and the broader HKH region, with the retreat of glaciers, frequent and intense natural hazards, and issues in water availability (Raghavan Krishnan et al., 2019; Kulkarni et al., 2013; Sabin et al., 2020; Wester et al., 2019a, 2019b). These climatic and environmental changes negatively affect the mountain livelihoods, which are highly dependent on the natural resource base and thus prone to the adverse impacts of these changes (Tuladhar et al., 2021). The research noted a stronger connection between climate change and human migration in areas where people's livelihoods are strongly dependent on the local environment (Piguet, 2022). In HKH, migration to lowlands or other regions serves as an adaptive strategy resulting in the diversification of mountain livelihoods (Gioli, Khan, Bisht, & Scheffran, 2014; Siddiqui et al., 2019). However, with the rising frequency and intensity of natural hazards, and changes in climatic conditions, the mountain livelihoods are further threatened and contribute to magnifying pre-existing socioeconomic vulnerabilities (Vaidya et al., 2019b). The poorest households who lack the resources and means to undertake migration may become 'trapped' or immobile (Black, Adger, et al., 2011; Zickgraf, 2018).

Generally, there is a lack of research information on climate change-induced migration among communities living in highlands (Gioli, Khan, Bisht, & Scheffran, 2014). Milan et al. (2015, p. 375) argue that "the relationship between migration and environmental and climatic changes is a crucial yet understudied factor influencing mountain livelihoods in the global South.” The livelihoods in the mountain ecosystems are dependent on natural resources such as forest, water land, and subsistence agriculture (Gentle & Maraseni, 2012; Gioli et al., 2019; Xu et al., 2009). According to Milan et al. (2015) academic literature, so far, has not addressed the global environmental change and specifics of migration among highland communities apart from few empirical case studies. Furthermore, notable reviews (Piguet, 2010, 2022) of climate migration scholarship confirm this, especially a very limited scholarship on climate change and migration nexus in Pakistan.

Migration has long been a prevalent phenomenon in northern Pakistan, encompassing regions such as Chitral, and has served as a historical response to various economic and social factors (F. Rahman, 2007). However, in recent times, labor, or seasonal migration functions as an adaptation strategy that households employ to cope with the diminishing agricultural productivity resulting from environmental shifts and the increasing incidence of extreme events, as depicted in studies (Gioli, Khan, Bisht, & Scheffran, 2014; Gioli, Khan, & Scheffran, 2014; Kreutzmann, 2012a) in Hunza and Yasin valleys in the Gilgit-Baltistan. Although some prior research explored migration patterns in the broader region, such as Lower Chitral and Upper Chitral (Holdschlag, 2000), seasonal mobility of herders (Kreutzmann, 2012b; Nüsser et al., 2012), and male out-migration from the Melph Valley (F. Rahman, 2007), there is a noticeable gap in the study of the climate-environment-migration relationship in the mountainous communities of northern Pakistan, particularly within the context of Chitral and the Eastern Hindu Kush region. Notable research conducted by the International Centre for Integrated Mountain Development (ICIMOD) has mainly focused on water-related hazards and their linkages with labor migration, as well as the role of traditional knowledge and local institutions in adaptation (S. Banerjee et al., 2011). Similarly, studies conducted in the neighboring Gilgit-Baltistan region explored the perceptions of climate change among local communities, its impacts on livelihoods, and the role of migration as an adaptation strategy (Gioli, Khan, Bisht, & Scheffran, 2014; Gioli, Khan, & Scheffran, 2014).

Despite these endeavors, the scholarship concerning the nexus of climate change, environmental degradation, and human (im)mobility remains remarkably limited in the mountainous regions of Pakistan, with a notable scarcity of research focused on Chitral and the Eastern Hindu Kush region. The complexities and nuances of climate-induced (im)mobilities in this region remain largely unexplored and represent a substantial research gap that necessitates further investigation.

2.4 Research Aims and Questions

In the context of climate change, multi-hazards, and human mobility in the Eastern Hindu Kush, and considering the limited empirical research, the primary objective of this thesis is to investigate the intricate interplay between climate change and human (im)mobilities within mountain communities. To accomplish this overarching goal, this study is guided by three interrelated research aims, each accompanied by a set of corresponding questions.

Research Aim 1: Investigate climate change and natural hazards, and their impacts on mountain livelihoods in the Eastern Hindu Kush region.

Research Aim 1 seeks to examine the multifaceted relationship between climate change, natural hazards, and mountain livelihoods. It aims to answer the following questions:

1. How do local people in the Lotkuh Valley perceive climate change, and what specific impacts does it have on their livelihoods? (Manuscript I)

2. What are the key socioeconomic, demographic, and environmental factors that influence the climate change perceptions in the Lotkuh Valley? (Manuscript I)

3. What are the observed trends in climate data (temperature, precipitation, and snow), and how do these trends compare with local perceptions? (Manuscript I)

4. What are the significant natural hazards, including multi-hazards, in Lotkuh Valley, and how do they affect the local livelihoods? (Manuscript I)

5. How has land cover in the Eastern Hindu Kush experienced abrupt changes over recent decades, and what are the spatiotemporal patterns of these changes across different sub-catchments? (Manuscript II)

6. What are the primary drivers contributing to the abrupt changes in land cover? Additionally, how can past flood events in the valleys be accurately detected, and how can the timing and magnitude of changes in land cover be effectively mapped? (Manuscript I, II & III)

Research Aim 2: Understand the climate (im)mobilities by exploring the interrelations between climate change and the environment as drivers of (im)mobilities.

Research Aim 2 explores the the complex interrelationships between climate change, environment, and human (im)mobilities, and aims to answer the following questions:

1. What are the characteristics of mobility in the Lotkuh Valley, and what factors drive human mobility and immobility? (Manuscript IV)

2. How can changes in precipitation and temperature, on the one hand, and extreme events, on the other hand, be translated into economic conditions for mobility as an adaptation strategy or immobility as a result? (Manuscript IV)

Research Aim 3: Develop an interdisciplinary framework for researching climate (im)mobilities using methods from social and physical sciences.

Research Aim 3 emphasizes the need to create an interdisciplinary research framework to explore the nexus between climate change and human (im)mobilities. The first two aims contribute to the development of this research framework, which aims to address the following question:

1. How can an interdisciplinary approach that combines quantitative and qualitative methods derived from physical and social sciences be employed to study the complex interplay between climate change and human (im)mobility? (Chapter 10)

Against the backdrop of the outlined research aims and questions, the forthcoming chapters on research areas and methodology lay the foundation for the scientific manuscripts.

3. Research Area

The research for this dissertation was conducted at two distinct scales: the regional and local levels. At the regional scale, the primary focus was on utilizing remote sensing for land cover change detection in the Eastern Hindu Kush region, which centered around Chitral and the neighboring areas. Additionally, the abrupt change detection method with a different dataset combined with the seasonal change detection method, was applied to the Fagita Lekoma district in the Northwestern Highlands of Ethiopia. This Ethiopian study serves as a methodological extension of the work in the Eastern Hindu Kush. More detailed information about this Ethiopian study area can be found in Manuscript III.

Simultaneously, the research involved investigations at the local level, with a particular focus on the Lotkuh Valley, which is situated within the Lower Chitral district. Furthermore, the validation of flood events detected through remote sensing was also carried out in the adjoining Ayun, Rumbur, and Bumboret valleys in the southern Chitral. The subsequent sections provide a brief overview of research settings.

3.1 The Eastern Hindu Kush

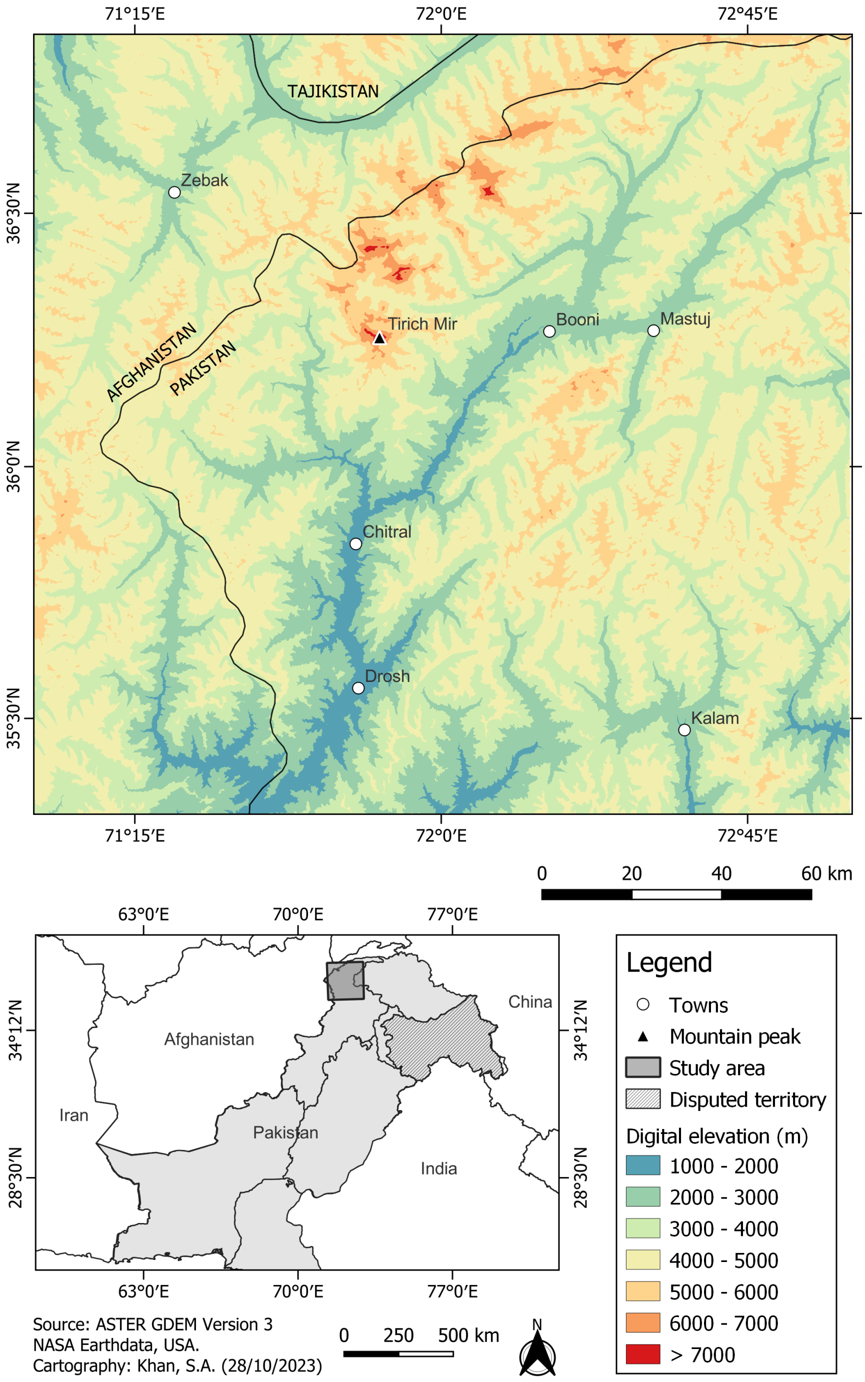
The Eastern Hindu Kush region is a geographically diverse area, surrounded by the Karakoram and Himalayan ranges in the east and southeast, and the Pamir mountains in the north and northwest. It extends from the Karambar Pass in the east to the Dorah Pass in the west. It mostly covers the Lower and Upper Chitral districts in the northern Khyber Pakhtunkhwa province of Pakistan. The study area for abrupt change detection in land cover encompassed parts of northern

Khyber Pakhtunkhwa province and the western Gilgit-Baltistan region, as well as the eastern regions of Nuristan and Badakhshan provinces in Afghanistan. The location of the area is depicted in Figure 3.1, with coordinates (35°20’24” and 36°43’48” N, and 71°19’12” and 72°59’24” E), covering approximately 22,000 km^2.

The region is characterized by its rugged terrain, featuring numerous mountains and glaciers, with Tirich Mir (7,708 m), the tallest peak in the whole of the Hindu Kush range. Most of the settlements are situated along the riverbanks of the Chitral River and its tributaries. Overall, the majority of the population is rural in the region. The largest urban center in the region is Chitral town (35°51’17.19” N, 71°47’21.74” E), which has approximately 49,000 inhabitants and is in the southwestern part of the study area.

Chitral, one of the highest altitude regions in the world, has over 40 peaks with more than 6,100 m of height (Aslam et al., 2021). The former Chitral district with a total area of 14,850 km^2 is situated in the Hindu Kush range and borders Afghanistan in the north and west, with Gilgit-Baltistan in the east and with Dir and Swat districts in the south. In 2018, the former district was split into two districts called Lower Chitral and Upper Chitral. Approximately, a large part of its terrain is covered with mountains and glaciers and some forest on the southern side. The historical evolution of the former Chitral state into the contemporary period is described in F. Rahman (2007). The largest river in the area is the Chitral River (also known as Kunar River) which enters Afghanistan in the west and then joins the Kabul River which is a tributary of the Indus River. Chitral and its river system are part of the upper Indus basin. Chitral is prone to several climatic hazards such as floods, erratic precipitations, flash floods, landslides, and glacial lake outburst falls (GLOFs) (Manuscript I). Several major flood events affected the area recently in 2010. 2015, 2022 and 2023.

The climate in Chitral, according to data from the Chitral weather station, exhibits an annual mean temperature of 16.1°C and receives a



Source: ASTER GDEM Version 3
NASA Earthdata, USA.
Cartography: Khan, S.A. (28/10/2023)

Figure 3.1: Overview of the study area in the Eastern Hindu Kush mountain region.

total annual precipitation of 405 mm, as recorded from 1970 to 2019[1]. The northern and northwestern portions of the study area experience lower precipitation, with a peak during the winter and spring seasons (Z. Syed et al., 2022). In contrast, the southern and southeastern parts receive more monsoon rains during the summer (Nüsser and Dickoré 2002). The southern region is marked by forests, while the central and northern areas of Chitral are predominantly treeless (Nüsser & Dickore, 2002; Zeb, 2019).

3.2 Lotkuh Valley

The Lotkuh Valley is situated in the Lower Chitral district of Khyber Pakhtunkhwa province, Pakistan (Figure 1). The valley was selected due to its exposure to multi-hazards, ongoing socioeconomic transformations, significant out-migration patterns, and practical considerations related to accessibility and research feasibility. Geographically, it falls within the Eastern Hindu Kush region, bordered by Afghanistan to the west, and it is accessible from Chitral town. The area consists of three sub-valleys: Karimabad, Garmchashma, and Arkari. The Lotkuh Valley is characterized by a challenging topography similar to other valleys in the Eastern Hindu Kush region with several high peaks exceeding 5,000 m.

As of the 2017 government census, the valley had a population of about 45,000 individuals, residing in approximately 6,600 households. The valley's livelihoods predominantly are agriculture-livestock based, with a mere 3% of the land deemed arable with landholdings in this area being relatively small, averaging around 2 hectares per household (Z. Ahmad et al., 2021). As in other parts of Chitral, crop cultivation primarily takes place in the floodplains and alluvial fans located within the narrow valleys, with a heavy reliance on irrigation water channeled from upstream sources (such as glacial and snow melt water) due to the deep riverbeds (Nüsser, 2001). Crops such as wheat, maize, rice, and pulses are staples, although potatoes have recently gained popularity as a cash

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[1] It is based on data from Chitral weather station. (*Source: Pakistan Meteorological Department*)

crop. Fruits like walnuts, grapes, apples, and apricots are also cultivated, and mono-cropping is prevalent, especially during the snow-covered winters in remote settlements. Livestock farming, historically essential for food security and income, has been declining, attributed partly to a shift towards cash crops like potatoes, which offer no fodder value to farmersas well as migration of youth to urban centers (Z. Ahmad et al., 2021). In addition to agriculture, labor, and out-migration play vital roles in the local economy. A significant proportion of households, around 43%, earn incomes below the national minimum wage of 17,500 Pakistan Rupees[2].

The Lotkuh Valley is highly susceptible to a range of hazards and was affected by multiple extreme events such as floods, earthquakes, landslides, avalanches, and rockfalls in some areas (Manuscript I). A staggering 83% of surveyed households have experienced the impacts of such extreme events in the past decade[2]. These events together with the changes in temperature and precipitation cause a toll on both human lives and livelihoods within the area, underscoring the need for comprehensive research on the impacts of climate change, extreme events on local livelihoods, and human (im)mobility in the area.

Figure 3.2: Pictures from Lotkuh Valley: View of Shershal Village on the left and a focus group discussion in Roi Village on the right.

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[2] According to a survey conducted in selected villages during this research in 2020.

3.3 Ayun, Rumbur, and Bumboret Valleys

The adjoining valleys of Ayun, Rumbur, and Bumboret are located in the southern Chitral between Chitral town and Drosh. Ayun Valley is situated along the Kunar River and is surrounded by mountains. The area is famous for its fruit orchards and is among the popular destinations for tourists. Rumbur and Bumboret valleys are among the three Kalash Valleys in Chitral, other than Birir. The Kalash or Kalasha people known for their unique culture, religion, and language, live in these valleys (Alberto Cacopardo, 1991; Augusto Cacopardo, 1991). This makes Kalash Valley as a major tourist attraction in Pakistan.

These valleys are prone to several natural hazards such as flash floods, landslides, earthquakes, and avalanches. The area was severely affected by recurrent riverine floods in Ayun and flash floods in parts of Rumbur and Bumboret valleys, especially, in 2010, 2013, and 2015 (S. H. Shah, 2015, 2016).

4. Research Methodology

This chapter provides an overview of the methodology and datasets that were collected and analyzed during this research. Detailed explanations of the methodologies and data collection and analysis procedures are provided in the respective manuscripts (see Chapters 6, 7, 8 & 9).

4.1 Methodological Approach

This dissertation employed a mixed methods approach involving several quantitative and qualitative methods (Bazeley, 2018; Creswell & Clark, 2017; Tashakkori et al., 2020; Tashakkori & Teddlie, 2021). The mixed method approach is rooted in the pragmatism philosophy, and as a research paradigm supports the use of various research methods and analysis techniques to produce knowledge useful for society (Hall, 2013; Yvonne Feilzer, 2010). Furthermore, mixed method approach is well suited for an interdisciplinary thesis such as this which encompasses both physical and human dimensions of climate change and human mobility. Research questions under the first aim were investigated using remote sensing approaches such as time series analysis of vegetation data to identify the abrupt change in the land cover and explore the flooding events in the Eastern Hindu Kush, as well as downscaling of the climate data to analyze the trends of temperature, snow and precipitation and other climatic parameters. To capture the societal aspects of climate change including its perceptions and exploring the natural extreme events and their impacts on mountain livelihoods, social science methods such as household level survey, interviews, and focus group discussions were employed in the Lotkuh Valley. The questions relating to the second aim were answered using qualitative and quantitative social science methods. The description of the data collection and analysis procedures is provided later in this chapter, and Manuscripts I & IV. Finally, the third aim was achieved by developing a research framework at the synthesis phase of this dissertation.

The remote sensing part continued throughout this research. Firstly, the study on detection of abrupt change in land cover in the Eastern Hindu Kush was carried out. The Ethiopian study on vegetation dynamics was based partly on the methodology employed in the Eastern Hindu Kush region. It showed that the abrupt change detection approach was compatible for a different region, and can be extended by adding seasonal analysis of the vegetation cover. Further details on the relevant datasets and methodologies can be found later in this chapter and also in the corresponding Manuscripts II & III.

The progress in the fieldwork for this research began in late 2019 with the design of the data collection tools which included formulating a questionnaire for the survey, guidelines for interviews, and focus groups. The ethical clearance for this research was received from the Ethic Commission of the University of Bayreuth. The Lotkuh Valley was selected for the fieldwork due to several important reasons including its appropriateness to the research topic, availability of field assistants and local contacts for the conduct of the survey and visits, diversity in terms of natural hazards, ongoing migration from the area and research resources to cover the logistics and related costs.

In the first phase of this research conducted between April and September 2020 in the Lotkuh Valley, a strategic approach was adapted to fieldwork. A total of 13 villages were carefully selected based on a range of characteristics, including remoteness, agroecological conditions, susceptibility to extreme events, natural hazards, physical accessibility, and logistical challenges. It is important to note that our purposive selection of villages implies that the survey results may not be statistically generalizable to the entire area. However, this approach allowed us to focus on diverse settings and issues present in our research area. Table

4.1 provides basic information on the selected villages.

Table 4.1: Basic information on selected villages in Lotkuh Valley.

Villages	Population[1] (2017 census)	Households[1] (2017 census)	Natural hazards[2]
Gobore	1028	114	Snow avalanche
Khatinj	206	30	Landslide
Madashil	735	108	Landslide, rockfall
Parabeg	1567	217	River erosion
Parsan	716	93	Rockfall, landslide, land subsidence
Roi	812	99	Debris flow
Shershal	485	78	Snow avalanche
Shoghore	491	69	River erosion
Shut	481	82	Landslide
Siyah Arkari	691	121	Debris flow, glacial outburst
Uchugol	987	146	Snow avalanche, rockfall
Wakht	410	58	Snow avalanche
Zhitur	786	109	Debris flow

[1] According to national census conducted by the Government of Pakistan in 2017.

[2] The information about natural hazards was initially based on the secondary sources but later also collected during the fieldwork in 2020.

All research activities in Lower and Upper Chitral districts are subject to the approval of local authorities. In this regard, special permission was sought from the concerned departments. The data collection phase began with the survey of households in the selected villages of Lotkuh Valley. Interviews and focus groups were also conducted in these villages. Follow-ups were conducted in the following years. Fieldwork to validate the identification of spatiotemporal aspects of floods detected through remote sensing data was also carried out in the Lotkuh Valley, and the Ayun, Rumbur, and Bumboret valleys south of Chitral town. More details on the field sites used for the validation of flood events are provided in Manuscript II. The data collection process was affected initially due to the onset of the Covid-19 pandemic and it was completed after the lockdowns were lifted from the area. Further details on the data collection and analysis procedures are provided below.

4.2 Biophysical Data

4.2.1 Landsat

The Modified Soil Adjusted Vegetation Index (MSAVI) was used to detect abrupt changes in the land cover in the Eastern Hindu Kush. MSAVI was selected due to its efficacy in minimizing soil background effects caused by the arid and semi-arid conditions, sparse vegetation, and the existence of bare soils in the study area, as outlined by Qi et al. (1994). MSAVI is derived from the reflectance in the near-infrared (NIR) and red spectral bands. In our case, the MSAVI dataset was derived from 811 images taken by the sensors Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) for Path 151 and Row 35 within the World Reference System-2 grid, covering the years 1988 to 2020. It is important to note that a comprehensive image archive from 1988 to 2020 was selected without applying any seasonal or time-specific filters.

The dataset underwent Level-2 Surface Reflectance processing, including radiometric, geometric, and atmospheric corrections, conducted by the United States Geological Survey (USGS). The MSAVI dataset features a spatial resolution of 30 meters and a temporal resolution of 16 days and was accessed from the Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) platform provided by the United States Geological Survey (USGS). Detailed information on the processing of this dataset is illustrated by the flowchart provided in Manuscript II.

4.2.2 MODIS

To derive snow trends, the Moderate-Resolution Imaging Spectroradiometer (MODIS) Snow Cover Product was used which is provided within the temporal range of 2001 to 2019. To address any missing data, a robust methodology was implemented. Specifically, instances with missing values were flagged, and a linear interpolation technique was applied using temporally neighboring data points. This interpolation approach has been validated in previous research (Haag et al., 2021; Zandler et al., 2020), confirming its effectiveness in ensuring data completeness and quality (Manuscript I).

Furthermore, the processing also involved the conversion of snow cover data into fractional snow cover. This transformation was carried out following the well-established methodology introduced by Salomonson and Appel (2006), which allowed for a more detailed understanding of snow cover dynamics.

Furthermore, the MODIS Terra satellite vegetation index product (MOD13Q1) spanning 2000 to 2020 was used to detect seasonal and interannual changes in vegetation cover (Manuscript III). This dataset has a spatial resolution of 250 m and was accessed from the National Aeronautics and Space Agency (NASA) archives in Google Earth Engine.

4.2.3 ERA5

The Eastern Hindu Kush region posed a significant challenge with its sparse distribution of climate stations, similar to neighboring peripheral mountain areas in the wider region (Haag et al., 2021; Zandler et al., 2019). The sole available official station, situated approximately 10 kilometers southeast of our research area in Chitral town, provided only monthly temporal resolution, which was insufficient for our rigorous climate analysis.

To address these challenges, ERA5-Land reanalysis datasets were opted for, which offer not only daily temporal resolution but also a more extensive and robust dataset. Furthermore, the ERA5-Land dataset exhibited enhanced performance compared to other climate data sources in regions proximate to our study area, providing greater confidence in the accuracy and completeness of the data.

4.3 Analysis of Biophysical Data

4.3.1 Abrupt change detection with BFAST

To detect abrupt changes in land cover in the Eastern Hindu Kush region, spanning from 1988 to 2020, BFAST (Breaks for Additive Season and Trend) was used for the time series analysis (Verbesselt et al., 2010). BFAST is a widely used method for detecting abrupt changes within remote sensing-based time series data and is useful even in the presence of seasonality and potential trends (Watts & Laffan, 2014). Furthermore, it exhibits resilience against noise (Verbesselt et al., 2010), making it a robust choice for the Eastern Hindu Kush.

BFAST has been previously employed to identify changes in deforestation (Lambert et al., 2013; L. Wu et al., 2020), vegetation patterns (Geng et al., 2019; Gholamnia et al., 2019), land use and land cover transitions (Hamunyela et al., 2020), and monitoring lake dynamics (L. Chen et al., 2014). However, its application had not extended to arid and semi-arid environments, such as the Eastern Hindu Kush, characterized by complex terrain, varying vegetation, and pronounced seasonality in precipitation. Additionally, the region's remote sensing data frequently contains noise due to persistent cloud cover, particularly during winter. BFAST's noise-resilient nature and its ability to handle strong seasonal variations render it a well-suited choice for our study.

BFAST decomposes time series data into three components: trend, seasonal, and remainder (or noise) (Verbesselt et al., 2010). However, the decomposition is carried out without requiring historical reference periods or presumptions about data trends. The trend component is characterized by a piecewise linear model with breakpoints (Verbesselt et al., 2010). BFAST also incorporates a piecewise linear seasonal model to capture the seasonal component, which can have breakpoints different from those in the trend component (Verbesselt et al., 2010). The implementation of BFAST involved processing the time series data using the BFAST package in the R statistical software. Irregular time series were transformed into daily and subsequently monthly data, enabling a more in-depth analysis of the data. Please refer to Manuscripts II & III for a detailed explanation of the methodology and workflow.

The time series analysis yielded valuable insights, including the identification of the number of breakpoints, their timing, and their magnitudes for each pixel. This analysis set the stage for further post-processing and validation, with a particular focus on abrupt changes associated with floods that disrupt vegetation in the valleys. The results were successfully validated through fieldwork data, high-resolution imagery, and photographic evidence, providing a robust workflow for studying land cover changes and their potential drivers. BFAST was applied to detect abrupt changes in land cover and show the spatiotemporal dynamics of the floods in Eastern Hindu Kush.

Furthermore, a partial replication of this methodology was conducted in the Ethiopian highlands, where it was employed to identify abrupt changes in trend components of the time series driven by reforestation campaigns. Moreover, this method was combined with TIMESAT (see Manuscript III) which detected seasonal analysis of the vegetation trend, to provide a holistic understanding of the vegetation dynamics in Ethiopia. The collective results from both studies underscore the versatility of BFAST as a tool for examining vegetation and land cover dynamics in diverse geographical regions.

4.3.2 Downscaling and trend analysis

The downscaling process involved the adjustment of the ERA5-Land data to align with station values, mitigating the documented bias between reanalysis temperature data and station data. This adjustment ensured that analyses maintained precision while preserving the integrity of trend calculations, which are crucial for our research.

To further ascertain the robustness of the trends observed in our data, we conducted a thorough comparison between trend results based on ERA5-Land and the Chitral station. The chosen climate variables, rooted in monthly resolution, included yearly Tmax, among others. This meticulous process verified the reliability of our trend analysis.

Furthermore, to address potential issues related to autocorrelation within time series data and ensure the accuracy of our findings, we implemented a specialized trend computation method. This method involved bias-corrected prewhitening, which is recognized for its effectiveness in removing autocorrelation before trend testing. The trend magnitude was calculated using Sen's slope, a robust method that provides precise trend assessments. Further details on the downscaling and trend analysis are provided in Manuscript I.

4.4 Social Data

4.4.1 Household survey

A household survey questionnaire was administered to 388 households in the 13 selected villages in the Lotkuh Valley with the assistance of a locally recruited research team. The village selection process is explained earlier in this chapter (4.1). The questionnaire contained close-ended questions and was piloted and tested in different villages. KoBoToolbox software was used to record the responses. Research assistants were given detailed orientation on the design and purpose of the survey questionnaire. A pilot phase was also carried out to train the research team and test the questionnaire. The app needs to be downloaded once on a mobile phone and then it does not require further access to the internet for recording responses. Once the survey forms were completed by each team member, they were shared with a database managed by the lead researcher.

The sample size for each village was determined in proportion to the 2017 Government of Pakistan census data. Households were selected within each village using a sampling interval. This survey covered respondents' socioeconomic and demographic attributes, their perceptions of temperature, precipitation, and seasonal pattern changes in the past twenty years, their experiences with past extreme events, the profile of migrants and non-migrants (in this case involuntary immobile), and various reasons of migration and immobility, among others. The survey also included collecting data on the types of extreme events and their impacts on livelihoods.

4.4.2 Interviews

In addition to the survey, qualitative data was gathered through a total of 41 interviews conducted in the Lotkuh Valley. Guidelines were prepared to guide the interview process with open-ended questions and prompts. These interviews explored the topics of migration, immobility, climate change, extreme events, and their consequences on local livelihoods. The interview data provided valuable insights into the subject matter, and the temporal scope was in alignment with the survey, covering the past two decades (2000-2019). Participants selection for the interviews was purposive covering migrants, non-migrants, farmers, teachers, and social activists from all the selected villages. The data collection process ended after reaching a stage of data saturation with no significant new information on the research topics.

4.4.3 Focus groups

To further enrich our data, seven focus group discussions were conducted within selected villages. These focus groups were strategically organized to ensure representation of the diverse characteristics of the study area. Participants included farmers, migrants, village elders, social workers, and individuals representing various segments of the community. The discussions covered topics such as agricultural practices, community experiences with past natural extreme events, the impacts of environmental changes on agriculture, and the dynamics of (im)mobility, along with the underlying drivers. The temporal focus for the focus group discussions corresponded to the survey and interviews, spanning the past two decades (2000-2019).

4.5 Analysis of Social Data

4.5.1 Quantitative analysis

For the quantitative analysis, the data collected through a household survey was utilized. This dataset was analyzed using descriptive statistics, allowing us to gain insights into the key features of the information collected. Descriptive statistics provided a clear overview of our findings, summarizing various variables related to the socioeconomic and demographic characteristics of the respondents, migration, non-migration, displacement, and analyses of the profiles of migrants and non-migrants, perceptions of climate change, and experiences with extreme events. The temporal focus on climate change perceptions in this quantitative analysis extended over the past two decades, from 2000 to 2019, which enabled the comparison of the perceptions with the analysis of climate trends. Moreover, the regression analysis was carried out to determine the influence of various factors that shape the climate change perceptions of the respondents.

4.5.2 Qualitative analysis

Qualitative analysis of the data gathered from interviews and focus groups was also conducted. These qualitative data sources provided valuable insights into the intricate nuances of climate change, extreme events, and their impacts on livelihoods, and human (im)mobility in the Lotkuh Valley. The interviews and focus groups, comprising 41 interviews and 7 focus groups, were transcribed in the Urdu language, subsequently reviewed, and transliterated into English for further analysis.

Qualitative Content Analysis (QCA) was employed as the analytical approach, following the methodology outlined by Kuckartz (2019). This involved systematically preparing the data for analysis, establishing main categories based on key research questions, and coding the qualitative data according to these main categories. Additionally, inductive subcategories were formed based on the passages associated with the main categories, enhancing the depth of our analysis.

The qualitative analysis was conducted within the computer-assisted qualitative data analysis environment of the MAXQDA software (Kuckartz & Rädiker, 2019). Through this process, significant themes and subthemes were identified, supported by excerpts from the transcripts to illustrate key findings. To enhance the reliability and validity of qualitative results, the findings from different focus groups and interviews were triangulated. This triangulation approach allowed cross-verification and strengthened the robustness of the qualitative insights.

Furthermore, the analytical strategies employed extended beyond individual data sources and encompassed the integration and synthesis of multiple data sources (Bazeley, 2018). This involved producing a coherent narrative that drew from various data sources, thereby providing a comprehensive perspective. By comparing and contrasting different data, the interpretations were enriched, offering a more holistic understanding of climate change and human mobility. Additionally, the merging of various data sources allowed me to create a detailed description and a comprehensive picture of the multifaceted relationship between climate change, extreme events, and human mobility in the Lotkuh Valley.

4.6 Software

Biophysical data was analyzed using R and its associated packages. Survey data was collected with KoboToolbox, and its statistical analysis was conducted using R and SPSS. Qualitative data was analyzed using MAXQDA.

PUBLICATIONS

5. Individual Contributions to the Manuscripts

Manuscript I (Chapter 6)

Title: Climate change impacts on livelihoods in the Eastern Hindu Kush: An interdisciplinary approach to integrating local perceptions and scientific evidence.
Authors: Saeed A. Khan, Harald Zandler, Oliver Sass
Journal: Scientific Reports
Status: Under review

Personal contributions:
Conceptualization 100%, data preparation 80%, data analysis 80%, methodology 80%, writing original draft 100%, review and editing 70%, and visualization 100%.

SAK conceptualized the study. SAK collected and analyzed the data. HZ carried out climate analysis and contributed to the writing of methodology and discussion. SAK wrote the original draft. Review and editing of the draft were done by SAK, HZ, and OS. Research was supervised by OS.

SAK is the corresponding author of this study.

Manuscript II (Chapter 7)

Title: Detecting abrupt change in land cover in the eastern Hindu Kush region using Landsat time series (1988-2020)

Authors: Saeed A. Khan, Kim André Vanselow, Oliver Sass, Cyrus Samimi.
Journal: Journal of Mountain Science, 19(6), 1699-1716; `https://doi.org/10.1007/s11629-021-7297-y`
Status: Published

Personal contributions:
Conceptualization 80%, data preparation 100%, data analysis 100%, methodology 80%, writing original draft 100%, review and editing 70%, and visualization 100%.

All authors conceptualized the study. SAK collected and analyzed the data. KAV assisted with software. SAK wrote the original draft. Review and editing of the draft were done by SAK, KAV, OS, and CS. OS and CS supervised the research.

SAK is the corresponding author of this study.

Manuscript III (Chapter 8)

Title: Vegetation Trend Detection Using Time Series Satellite Data as Ecosystem Condition Indicators for Analysis in the Northwestern Highlands of Ethiopia
Authors: Bireda Alemayehu, Juan Suarez-Minguez, Jacqueline Rosette, and Saeed A. Khan
Journal: Remote Sensing (2023), 15(20), 5032; `https://doi.org/10.3390/rs15205032`
Status: Published

Personal contributions:
Data preparation 20%, data analysis 50%, methodology 50%, and revision 10%.

BA, JS, and JR conceptualized the study. BA and SAK analyzed the data. SAK conducted abrupt change detection and contributed to the revision. BA wrote the original draft. Review and editing of the draft were done by BA, JS and, JR. JS and JR supervised the research.

SAK is the co-author of this study. BA is the corresponding author of this study.

Manuscript IV (Chapter 9)

Title: Climate (im)mobilities in the Eastern Hindu Kush: The case of Lotkuh Valley, Pakistan.
Authors: Saeed A. Khan, Martin Doevenspeck, Oliver Sass
Journal: Population and Environment (2024). 46:2; `https://doi.org/10.1007/s11111-023-00443-2`
Status: Published

Personal contributions:
Conceptualization 100%, data preparation 80%, data analysis 80%, methodology 80%, writing original draft 100%, review and editing 70%, and visualization 90%.

SAK conceptualized the study. SAK collected and analyzed the data. MD and OS contributed to the methodology and discussion. SAK wrote the original draft. Review and editing of the draft were done by SAK, MD, and OS. MD and OS supervised the research.

SAK is the corresponding author of this study.

6. Manuscript I: Climate Change Impacts on Livelihoods in the Eastern Hindu Kush: Integrating Local Perceptions and Biophysical Data

Outline

Bibliographic Information

Khan, S. A., Zandler, H., Sass, O. (under review): Climate change impacts on livelihoods in the Eastern Hindu Kush: Integrating local perceptions and biophysical data. Scientific Reports.

Article Adaptation

The article is currently in review. The contents of the original version had to be slightly modified for its inclusion in this dissertation, including the numeration of sections, figures, tables, and equations had to be adjusted.

Abstract

Climate change affects mountain communities through its adverse impacts on both natural and human systems. Additionally, the livelihoods are exposed to the severe and interconnected impacts of multiple hazards and associated extreme events. This study integrates perceptions of climate change and natural hazards with the analysis of biophysical data, focusing on the overlapping effects in mountain regions like the Eastern Hindu Kush, where local livelihoods rely on ecosystem services vulnerable to cryospheric and climatic changes. The study addresses a research gap in the assessment of climate change and natural hazards in the region, employing an interdisciplinary approach in Lotkuh Valley, north Pakistan. Using household surveys, interviews, and focus groups, we assessed local perceptions and impacts of extreme events, while climate trends were analyzed using ERA5-Land and MODIS snow products. The BFAST method was employed to unveil the spatiotemporal aspects of floods through the analysis of Landsat-derived MSAVI. Findings reveal that most respondents perceived changes in temperature and precipitation and their impacts on local livelihoods. These perceptions are influenced by education, access to agricultural land, and experience of extreme events. Extreme events severely impact local livelihoods with floods emerging as the major hazard in the area and have connected impacts with landslides and avalanches. The integrated research approach showed the convergence and divergence between local perceptions and climate trends. Overall, this study provides fresh insights into the impacts of climate change and natural hazards on local livelihoods and significantly contributes to a better understanding of mountain vulnerabilities in the region. It offers practical implications for policy formulation and climate change adaptation in the Eastern Hindu Kush region and similar areas.

6.1 Introduction

Climate change is affecting weather and climate extremes globally (Seneviratne et al., 2021). It has caused widespread adverse impacts on both natural and human systems by reducing food security and increasing water scarcity through warming and changes in precipitation (IPCC, 2023). Climate change also negatively affects the health, livelihoods, and community infrastructure, especially the socially and economically marginalized societies (Ebi et al., 2021; IPCC, 2023). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land noted that the increase in the frequency and intensity of climate extremes have contributed to land degradation and desertification in many parts of the world (Masson-Delmotte & Pörtner, 2022).

The Hindukush, Karakoram, and Himalaya (HKH) region is vulnerable to the impacts of climate change as the cryosphere and hydrological regimes are changing (You et al., 2017). HKH is experiencing warming more than the global average (Kraaijenbrink et al., 2017). Glaciers in most parts of HKH experienced thinning, retreat, and loss of mass in the past decades (Bolch et al., 2019). Cryosphere in the HKH region serves as an important water storage mechanism and a critical source of irrigation water in the streamflow (Bolch et al., 2019; Mukherji et al., 2019). In terms of temperature, the HKH region has experienced increasing extreme warm events, decreasing extreme cold events, and increased trends in extreme values and the frequencies of temperature-based indices (Krishnan et al., 2020; You et al., 2017). Moreover, the frequency of flooding, both glacial-lake outbursts and run-off floods, has increased in the region (Molden et al., 2022; Nie et al., 2021).

The mountain livelihood in the HKH region, particularly crop-livestock agriculture depends on ecosystem services that are fragile in nature (Wu et al., 2014). Population growth, rapid urbanization, over-grazed pastures, soil erosion, and deforestation have contributed to the steady decline in the natural resource base (Gioli et al., 2019; Nüsser, 2001; Nüsser & Dickoré, 2002). Changes in weather and climate increase the vulnerability of mountain livelihoods, which is further exacerbated by mountainspecificities such as socioeconomic marginalization, inaccessibility, and fragility (Gioli et al., 2019). Rise in temperatures and changes in rainfall patterns cause harvest delays, crop pests, and low agricultural yield (Ajani & van der Geest, 2021; Hussain et al., 2016; Vogel et al., 2019). In addition, extreme events triggered by natural hazards pose a serious threat to human lives and often cause displacement (Ajani & van der Geest, 2021). These events also cause the degradation of scarce agricultural land and the destruction of standing crops (Ajani & van der Geest, 2021). Moreover, the irrigation network, housing, and infrastructure are also disrupted by these extreme events (Ajani & van der Geest, 2021; Hussain et al., 2016; Nüsser, 2001). The occurrence of compound events that result from multiple hazards causes severe socioeconomic impacts and increases household food insecurity (Hussain et al., 2016; Rusk et al., 2022). They are caused by different combinations of hazards (e.g. floods, landslides, and avalanches) and are driven by both physical and societal drivers (Raymond et al., 2020).

Perceptions of climate change are shaped by a multitude of factors such as personal experiences with climate change particularly with extreme events, age, gender, education, and political orientation among other factors (Lujala et al., 2015; Poortinga et al., 2019; Sloggy et al., 2021; Weber, 2016; Xie et al., 2022). In the HKH region, several studies on local perceptions of climate change and its impacts including natural hazards, particularly floods were conducted (Ajani & van der Geest, 2021; Banerjee, 2015; Bhatta et al., 2019; Dilshad et al., 2019; Hussain et al., 2016; Joshi et al., 2013). These studies show that the local populations perceived climate change. Similarly, trends of climate variables such as snow, precipitation, and temperature were analyzed in many studies (Ren et al., 2017; Sun et al., 2017). Most of the previous studies used climate data from meteorological stations which are very sparse in HKH and have uncertainties due to valley altitudes and microclimates in the area (Dahri et al., 2021; Singh et al.; Spies, 2020). Gridded products, particularly the 5th generation European Centre for Medium-Range Weather Forecasts ECMWF Re-Analysis (ERA5), are found to provide better estimates (Dahri et al., 2021; Syed et al., 2022).

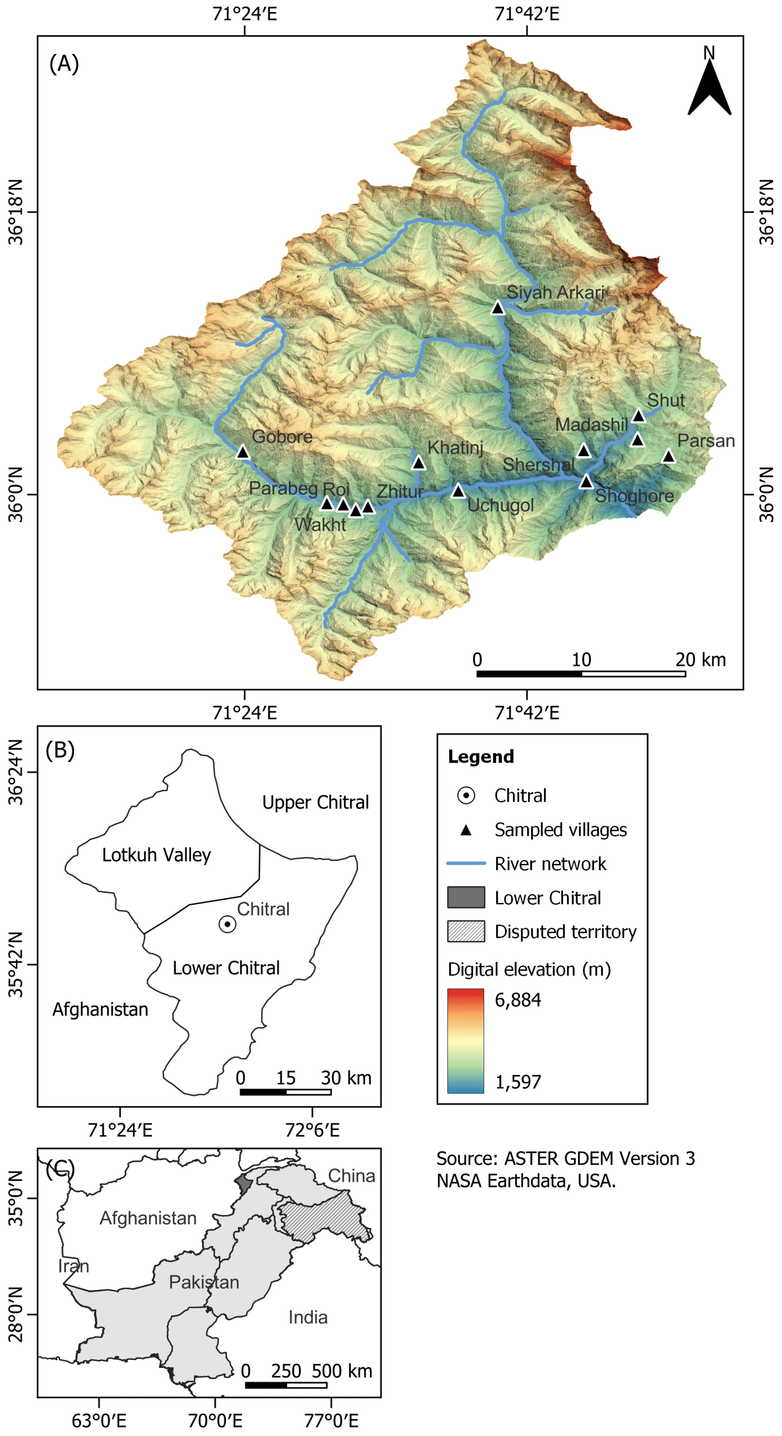
Recently, research approaches have also focused on the integration of climate change perceptions with hydrometeorological analysis of climate data. Studies that combine both perceptions and climate trend analysis are few in HKH and mostly compared perceptions with climate data from meteorological stations such as in India (Macchi et al., 2015; Sharma & Shrestha, 2016), Nepal (Pandey et al., 2019), and Nagar District(Spies, 2020) in the Gilgit-Baltistan region in Pakistan. Studies were also undertaken in other regions to integrate perceptions of climate change with climate trends such as in northern Ghana (Guodaar et al., 2021), the Qilian Mountains of northwest China (Xie et al., 2022), the Pamir Mountains of Tajikistan (Haag et al., 2021), and the Punjab Province of Pakistan (Abid et al., 2019), among others. However, such studies offer little insight into the integration process itself which often requires an interdisciplinary approach to combine different research methods. Moreover, extreme events which are also influenced by climate change are not included in the integrated studies.

The study area is located in the Eastern Hindu Kush in northwest Pakistan, which is characterized by an arid and semi-arid environment (Nüsser & Dickoré, 2002), high mountains, and seasonal extremes of precipitation and temperature (S. Ahmad et al., 2020; Syed et al., 2022). This region is particularly interesting to study climate change perceptions in relation to hydrometeorological data because there are indications of different climate trends compared to the global situation or other areas in HKH (Ougahi et al., 2022), such as increases in snow or decreases in summer temperatures (S. Ahmad et al., 2020; S. Ahmad et al., 2021). In addition to the changes in the cryosphere and exposure to natural hazards similar to HKH, the valleys experienced abrupt changes in land cover (Khan et al., 2022). There is a lack of research on the perceptions of climate change and its impacts on livelihoods in the Eastern Hindu Kush region. In addition, no study integrated perceptions of climate change with the analysis of climate data in this region. To address these knowledge gaps, we studied climate change impacts on mountain livelihoods and integrated the perceptions of climate change and the impact of extreme events with the analysis of biophysical data. To achieve this, we use an interdisciplinary approach that combines data from household survey, interviews, and focus groups with the analysis of vegetation and climate data. The main objectives of the study are as follows: (1) assess the perceptions of climate change, and analyze the factors that shape these perceptions; (2) analyze trends in temperature and precipitation and compare if the local perceptions match with the climate trends; (3) analyze the impacts of climate change and extreme events on local livelihoods; and (4) detect past flood events using remote sensing approach and compare the timing and impact of the event with survey and interview data. This study provides insights into climate change impacts in the Eastern Hindu Kush. It also highlights the convergence and divergence between local perceptions and climate trends and builds a better understanding of climate change. The findings of the study are useful for designing and implementing climate change adaptation strategies in the Eastern Hindu Kush.

6.2 Methods

6.2.1 Study area

This research was conducted in the Lotkuh Valley which is located in the Lower Chitral district of Khyber Pakhtunkhwa province of Pakistan (Figure 6.1). We focused on this area due to its exposure to multi-hazards, socioeconomic changes, out-migration, and other practical considerations such as accessibility and feasibility for this research. The area can be divided into three sub-valleys of Karimabad, Arkari, and Garamchashma with elevation ranging from 1,600 m to over 6,000 m. Geographically, it is situated in the Eastern Hindu Kush region, borders Afghanistan on the west, and is accessed from Chitral town. The government census in 2017 estimated its population of approximately 45,000 inhabitants and 6,600 households.



Source: ASTER GDEM Version 3
NASA Earthdata, USA.

Figure 6.1: Map of the study area. A) shows sampled villages in the Lotkuh Valley; B) the location of Lotkuh Valley in the Lower Chitral district; and c) Lower Chitral in northwest Pakistan.

Agriculture is one of the main sources of livelihood. Only 3% of the land is cultivable and the farmers have small landholdings with an average size of 2 hectares (Z. Ahmad et al., 2021). About 88% of households in the valley own agricultural land (Table 1). The crop cultivation takes place in the flood plain and alluvial fans in the narrow valleys similar to other mountain areas of the Eastern Hindu Kush (Nüsser, 2001). . The area also receives snow in the winter, and mono-cropping is practiced in many areas. In addition to crop cultivation, livestock farming also plays a significant role in meeting household food security and income generation. Recently, livestock farming has seen a decline in the valley, due to a shift to more cash crops such as potatoes which have zero fodder value for farmers (Z. Ahmad et al., 2021). Overall, 43% of households earn below the national minimum wage of <17,500 Pakistan Rupees (Table 1).

Lotkuh Valley is also prone to multiple hazards and associated extreme events including floods, landslides, earthquakes, avalanches, and rockfall. About 83% of surveyed households were affected by an extreme event in the past 10 years (Table 6.1). The extreme events adversely affect human lives and livelihoods in the area.

6.2.2 Research design and approach

The research design is informed by the sustainable livelihoods framework (Natarajan et al., 2022; Scoones, 1998). It explains the intricate ways in which people combine various resources and strategies to achieve sustainable livelihoods (Scoones, 1998). It emphasizes the importance of livelihood resources including human, social, economic, and natural capital, which are leveraged to pursue different livelihood strategies in a specific context (Scoones, 1998). Livelihoods are deemed sustainable when they can cope with and recover from external shocks or stressors such as extreme events, and main or enhance them without undermining the natural resource base (Serrat, 2017).

This study employed a mixed-methods research design (Bazeley, 2018; Tashakkori et al., 2020; Tashakkori & Teddlie, 2021) which combined quantitative and qualitative methods. The quantitative data were collected and analyzed using a household survey, trend analysis of climate data, and time series analysis of remotely-sensed vegetation. While qualitative interviews and focus groups were conducted and analyzed to enrich descriptions. To integrate the local perceptions of climate change and its impacts on mountain livelihoods with the biophysical data, we propose a research framework provided in Figure 6.2. The framework illustrates that climate change (i.e., changes in temperature, precipitation, and seasonal patterns), and extreme events (e.g., floods, landslides, avalanches) impact local livelihoods. Agricultural production, livestock, and land are central to the livelihoods of mountain people (Gioli et al., 2019). These livelihood strategies are also shaped by broader socioeconomic and political contexts such as access to information, institutional services, and markets among others. Household and personal characteristics of its members such as gender, age, education, household size, income, and landholding are crucial for livelihood strategies. These characteristics also influence the perceptions of climate change and extreme events (Weber, 2016).

The framework draws on the sustainable livelihoods approach (Natarajan et al., 2022; Scoones, 1998) as well as the climate change perception literature and is grounded in previous research on climate change impacts on the mountain livelihoods in HKH, discussed earlier. Methodologically, it combines top-down approaches such as downscaling of regional climate models and remote sensing to analyze vegetation data, with bottom-up approaches (survey, interviews, and focus groups) for the study of local perceptions of climate change. The framework provides an interdisciplinary approach to integrate climate change perceptions which are analyzed methods from social sciences and analysis of biophysical data using physical science methods.

The study was approved by the Research Ethics Committee at the University of Bayreuth, and all methods were performed in accordance with the relevant guidelines and regulations.

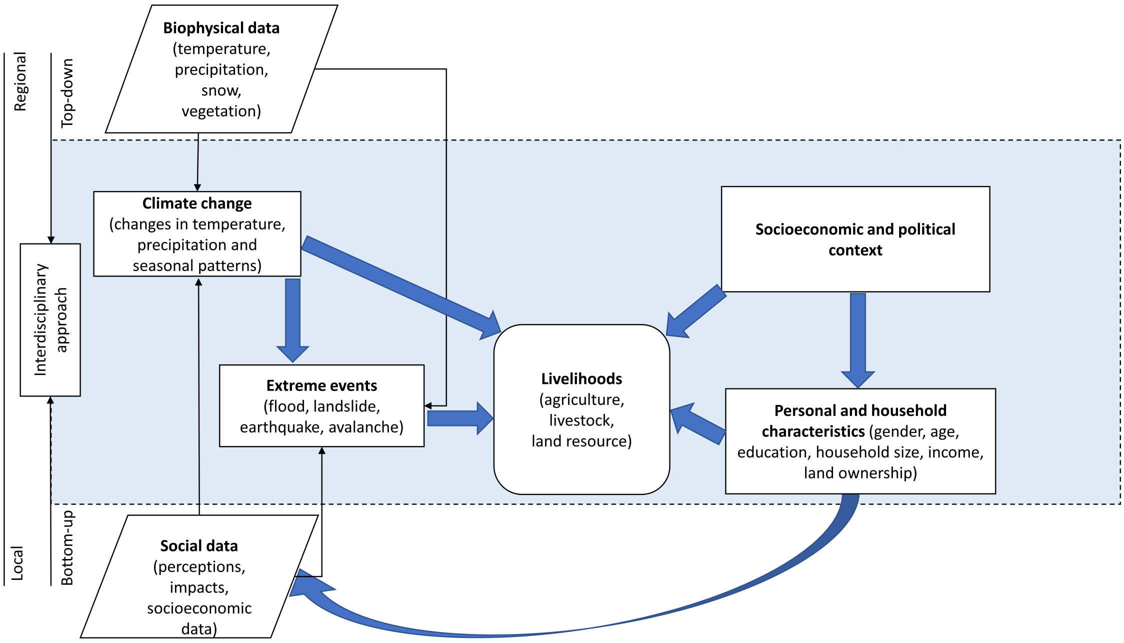


Figure 6.2: Research framework. An interdisciplinary approach to integrating perceptions of climate change and its impacts on livelihoods and biophysical data.

Field data collection and analysis

In the first phase, fieldwork was carried out in the Lotkuh Valley from April – September 2020. A total of 13 villages were purposively selected to have a balance of various characteristics (remoteness, agroecological conditions, extreme events, natural hazards, physical access, and logistical challenges). With the assistance of a research team recruited locally, a survey questionnaire was administered to 388 sampled households. The sample size for each village was proportionally distributed in each village based on the census conducted by the Government of Pakistan in 2017. The households were randomly selected using the sampling interval in each village. The survey collected data on the socioeconomic and demographic characteristics of respondents and households, perception of changes in temperature, precipitation, and seasonal patterns, experiences of past extreme events, their types, and impacts on livelihoods. Survey data was analyzed using descriptive statistics. To analyze what factors, shape climate change perceptions, regression analysis was conducted. To set up the regression model, a response variable (perceived climate change) was created from two existing variables (perceived change in temperature, and perceived change in precipitation). Since the dependent variable is a binary and the goal is to predict the probability of perceptions shaped by several predictor variables, we used a logistic regression model similar to other studies on climate change perceptions (Babanawo et al., 2023; Poortinga et al., 2019). The predictors in our model are 2 continuous (age and household size) and 6 categorical (gender, education, agricultural income, monthly income, land ownership, and affected by extreme events) variables. The descriptive statistics of these variables are provided in Table 6.1. Qualitative data on climate change, extreme events, and their impacts on livelihoods was collected using 41 interviews and 7 focus groups. Qualitative data were transcribed, translated, and further analyzed using a qualitative content analysis approach. Data on perceptions was collected covering the past twenty years (2000-2019) and impacts of extreme events in 10 years (2010-2019), in a similar approach to Gioli et al. (2014) and Hussain et al. (2016) Survey data was analyzed in IBM SPSS Statistics (Version 26) and R (Version 4.2.3) and qualitative data in MAXQDA (Version 2022).

Table 6.1: Descriptive statistics of the surveyed households in Lotkuh Valley.

Characteristics	**Statistics**
Number of respondents (N)	388
Number of villages	13
Age (Mean: SD)	40.8: 15.4
Gender (F: M)	97: 291
Education	114 (29.4)
College/ university, n (%)	129 (33.2)
Primary – secondary, n (%)	145 (37.4)
Not educated, n (%)	

Characteristics	**Statistics**
Household size (Mean: SD)	7.5: 2.7
Monthly income (Pakistan Rupees)	127 (32.7)
>30,000, n (%)	93 (24.0)
17,500 - 30,000, n (%)	168 (43.3)
<17,500, n (%)	
Ownership of agricultural land, n (%)	342 (88.1)
Affected by an extreme event, n (%)	321 (82.7)

Climate data and analysis

To compare local people's perception of climate change with physical climate parameters, we selected Climate Change Indices outlined by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Brown et al., 2010; Karl et al., 1999; Peterson et al., 2001) to derive climate data trends that closely match the topics of the survey. Respective climate indices for the comparison were frost days (days with minimum Temperature $< 0°C$) as a reference for winter duration, summer days (defined as days with maximum Temperature > 20 °C) for summer duration, the simple precipitation intensity index (Peterson et al., 2001) and yearly precipitation to derive rainfall variables, yearly and seasonal trends of the mean (Tmean), maximum (Tmax) and minimum (Tmin) temperatures, and snow cover as a proxy for snowfall and intensity. Therefore, climate data with a daily resolution is required to calculate several of the key climate indices.

A major challenge in climate data analysis in the research area is the very low density of long-term climate stations, a situation comparable with neighboring peripheral mountain areas (Haag et al., 2021; Zandler et al., 2019). The only available official station is located in Chitral (Pakistan Meteorological Department), approximately 10 km Southeast of the research area and with a monthly temporal resolution. At this station, the climate parameters Tmax, Tmin, and precipitation are measured and were obtained for the period 1970 to 2019. However, given the insufficient temporal resolution and the associated challenges of station-based climate data in peripheral mountain areas in High-Asia (Haag et al., 2021; Zandler et al., 2019), we selected the reanalysis datasets ERA5-Land (Muñoz Sabater, 2019) for conducting the numerical analysis of climate trends. Furthermore, the reanalysis dataset also showed increased performance compared to other climate data sources in regions in close proximity to the research area and with similar conditions (Zandler et al., 2020) or other parts of the HKH (Baudouin et al., 2020), although absolute differences to station values can still be high (Zandler et al., 2019). To address the documented large bias between reanalysis temperature data and station data, we additionally performed a lapse-rate downscaling approach following the method outlined in Haag et al. (2021). For this approach, we also used resampled pressure-level information from the ERA-5 product (Hersbach et al., 2023). Additionally, we performed bias adjustment by calculating the bias between monthly downscaled reanalysis temperatures and temperatures at the Chitral station to correct the absolute values of the reanalysis dataset. Respective adjustment only changes absolute values and climate indices connected to absolute temperature values but does not influence trend calculations due to their linear nature. After downscaling and bias correction, we averaged the required parameters over the research area. Finally, we checked for the robustness of the trends by comparing trend results of selected climate variables that are based on monthly resolution, such as yearly Tmax, between ERA-5 and Chitral station and found satisfying agreement.

As snow trends can also be derived using optical remote sensing methods, we included an analysis of the daily MODIS Snow Cover product (Hall & Riggs, 2021). Missing values were flagged and linearly interpolated using temporally neighboring data, as this approach showed good results in existing research (Haag et al., 2021; Zandler et al., 2020). Finally, the product was converted to fractional snow cover using the approach of Salomonson and Appel (2006) and averaged over the research area.

After spatial and temporal averaging, we calculated trends for the period 1970-2019 for the ERA5-Land based variables, and for the period 2001 to 2019 for snow cover. The respective time span was selected to represent the period before the survey year. As autocorrelation in the time series may lead to false rejections of the null hypothesis of no trends (Hamed, 2009; Zandler et al., 2019), we applied an adapted trend computation method using bias-corrected prewhitening presented in Hamed (2009) and implemented in the R-package modifiedmk (Patakamuri & O'Brien, 2021). Thereby, autocorrelation is removed before the trend test, and the trend magnitude is calculated by Sen's slope, which is more robust in comparison to the linear least squares method (Haag et al., 2019).

Remote sensing-based abrupt change detection in vegetation

To derive corresponding information on abrupt vegetation changes that may represent flooding, we accessed the Modified Soil Adjusted Vegetation Index (MSAVI) derived from 811 images of the Landsat sensors (Landsat 4-5 Thematic Mapper, Landsat 8 Enhanced Thematic Mapper Plus, and Landsat 8 Operational Land Imager) for the period of data availability 1988 to 2020. The images were selected for Path 151 and Row 35 (World Reference System-2) and downloaded from the United States Geological Survey's (USGS) Earth Resources Observation and Science (EROS) Center for Science Processing Architecture (ESPA) platform. Data belongs to Level-2 Science Products which are processed for radiometric, geometric, and atmospheric corrections (USGS, 2015). We detected known flood events using the Breaks for Additive Seasonal and Trend (BFAST) method to demonstrate its impact on the land cover. It was implemented in R-package BFAST ("Breaks for Additive Season and Trend [R Package Bfast Version 1.6.1]," 2021). BFAST is a time series analysis method widely used in the remote sensing community for the detection of abrupt changes (Verbesselt et al., 2010). Our pre-processing of MSAVI, application of BFAST, and post-processing of results are based on the approach illustrated in Khan et al. (2022) in the Eastern Hindu

Kush region. We used BFAST to triangulate the timing of flood events and show the spatial impact on vegetation in the floodplain. Moreover, the changes in magnitude show the intensity of the impact on the land cover.

6.3 Results

6.3.1 Perceptions of climate change and its impact on livelihoods

About 98% of surveyed households perceived a change in climate over the past 20 years. 96% of households (n=372) reported that they observed a change in the temperature. Similarly, 92% of households (n=356) reported a change in precipitation over the same time.

Survey respondents were asked about the manifestations of change in temperature through its impact on length or duration and perceived temperature in summer and winter seasons. The results are shown in Figure 6.3 (A). 67% of respondents (n=261) reported an increase, and 26% (n=100) reported a decrease in winter temperature. While 63% of respondents (n=243) said summer temperature increased and 28% of respondents (n=109) termed a decrease in the temperature during summer. About 36% perceived an increase and 43% of respondents perceived a decrease in the length or duration of the winter season. An increase in the length of the summer season was perceived by 52% of respondents (n=200) compared to 27% of respondents (n=104) who perceived a decrease in the summer duration.

Precipitation-related changes are categorized into rainfall and snowfall as shown in Figure 6.3 (B). An increase and decrease in rainfall were reported by 49% (n=162) and 32% (n=154) of respondents, respectively. As far as snowfall is concerned, 62% of the respondents (n=241) said it decreased and 24% (n=92) associated it with an increase. Regarding the intensity of precipitation events or spells, 47% (n=183) of respondents termed an increase in rainfall and 58% (n=224) stated a decrease

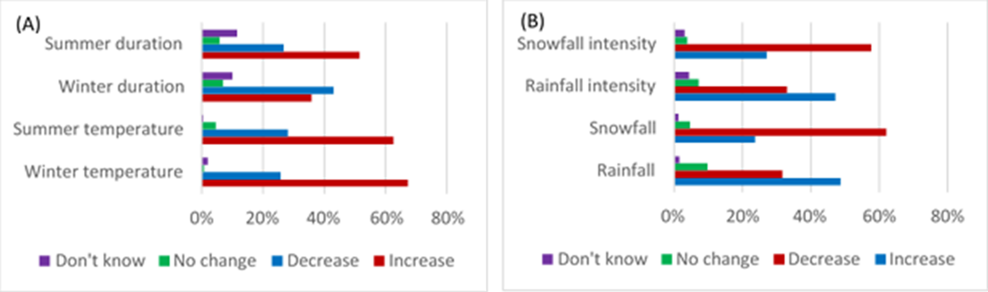


Figure 6.3: Manifestations of climate change: A) changes in temperature, and B) changes in precipitation.

in snowfall events.

People noticed that the changing weather patterns (changes in precipitation and temperature) had implications for their livelihoods. The changes in weather patterns and the duration of seasons affect crop productivity in the area. Interview respondents perceive that the higher than usual temperatures in the summer result in premature drying of crops and earlier ripening resulting in smaller grain size. People also linked hot summers and changes in the onset of seasons with various crop pests and diseases. Together, all these effects lead to low crop yield thus affecting the income and food security of the households. Wheat, which is the main staple crop, is negatively affected by the rise in summer temperatures resulting in its poor health and low yield. Hot coupled with dry weather exacerbates the low productivity of crops. The farmers mentioned the wheat crop in 2020 gave a low yield due to heat stress in that year. To illustrate this, a farmer's account which highlights the impact of changes in weather on the crops in 2020 is given below:

> *"In the past, crops and fruits were not infected with diseases. Now we also spray apricot and apple. The potato crop was damaged this year. We call it 'gronch' which means [crop] drying out, and 'rashka' which is fodder for animals also vanished. Wheat also dried out this year."* (Interviewee, Gobore, 2020)

It was noted that the harvesting period varies between villages in the Lotkuh Valley. Moreover, the villages at higher altitudes such as Arkari, Khatinj, Gobore, Parsan, and Shershal have harvesting periods starting later than others at the lower altitudes. Farmers' accounts suggest that the changes in weather patterns are causing a shift in the harvesting period, which is moving earlier. People in the study area noticed a decline in the snowfall, which has implications for water availability since the irrigation network and power generation rely on the water from glacial and snowmelt. For instance, people in Arkari mentioned that their village used to receive about 1 meter of snow in the past, and now it is one-third of this. They further explained that this winter (2019-2020) snow was so little that they did not have to clear it. Moreover, the snow in the past used to stay for quite a long duration, as indicated by the following statement:

> *"In former times, when it used to snow a lot then there was a lot of water. It [snow] used to take more time to melt. Now snow melts early... water shortages are happening. Water [scarcity] is becoming an issue."* (Interviewee, Shut, 2020)

The patterns of rainfalls have also changed. People mentioned their experience of more rainfall occurring in the spring than in the summer months in the past. But now they noticed that the rains in the spring season reduced while summer rainfall has increased. The people also noticed that the monsoon in the area is a relatively new phenomenon for them. Farmers find spring rains more useful as they irrigate the lands which are cultivated, and monsoon rains are more harmful, mainly causing floods and affecting the standing crops ready for harvesting. Moreover, they noted that the monsoon causes intense rainfall events in the summer which further increases the risk of flash flooding and landslides in the area. Intense rainfall events in the summer severely affect the standing crops and, in some cases, result in crop failure. The accounts of a farmer about changes in the rainfall patterns are given in the following:

> *"There is more rain in March-April but now there is less rain in March-April but if there is rain in June-July then it is monsoon rain. Monsoon rains did not occur in Chitral*

> *earlier and due to these monsoon rains flash floods come, it has intensified which cause a lot of damage to people and houses, so now it is going on."* (Interviewee, Shershal, 2020).

When he was further enquired about the monsoon rains, he stated:

> *"It [monsoon] is brand new and it rains at the time of harvesting wheat. It spoils the ready crop of wheat."* (Interviewee, Shershal, 2020)

People also observed the intense snowfall events together with earthquakes, which are frequent phenomena in the Lotkuh valley and neighboring regions of the Hindu Kush, compound avalanches. Similarly, the erratic rainfall events during the spring season, especially in March – April, also trigger avalanches. People also noticed that the shortage of rainfall and snowfall causes water scarcity in some areas as the water supply is dependent on glacial and snow melt. It was also mentioned that the decrease in snowfall has led to a reduction in the avalanche hazard in some areas, such as witnessed below:

> *"In the past, we had avalanches, but nowadays due to low snowfall we don't have such catastrophes in our area."* (FGD participant, Gobore, 2020)

Farmers also perceived variability of rainfall over the years. They regarded the year 2020 as a dry and hot year which negatively affected the yield of the wheat crop, as mentioned earlier. Overall, people often mentioned an increase in extreme rainfall events, particularly in the summer. However, a few years had received heavy rains, and then a few years had little or no rain. Several participants of interviews and focus groups described the monsoon as a relatively new phenomenon in the Lotkuh Valley and also attributed it to the erratic rainfalls and flash floods.

It was noted that the changes in the rainfall and snowfall also affect the water availability in the area. Most of the agricultural lands are supplied with irrigation water sources from the glacial melt. The lands which are fed through the irrigation channels from the main tributaries of the Lotkuh River have sufficient access to irrigation water. The agricultural fields which are more dependent on irrigation water from springs and channels sourced to snow melt face water scarcity due to reduced snowfall. Farmers also associated the hot years with more glacial melting and with the floods in their villages, as indicated below:

> *"Flood, the glacier of Dhirgol which I am talking about, it comes from there and it is definite [flood] when the summer is warmer. When the temperature is high then it melts more."* (Interviewee, Siyah Arkari, 2020)

6.3.2 Factors shaping perceptions of climate change

To assess the relationship between the socioeconomic characteristics of the surveyed households and their perceptions of climate change, logistic regression was used (Table 6.2). Socioeconomic factors such as gender, age, education, farmers, household size, income from agriculture, monthly income, ownership of land, and affected by an extreme natural event were the independent variables. The regression results show that only three independent variables (no education, land ownership, and affected by extreme events) are significant (p-value: 0.039, 0.042, 0.000, respectively). Those who have no education compared to college or university graduates are less likely to perceive climate change. The farmers who own landholdings also perceived climate change. Moreover, people who are affected by natural hazards and extreme events are more likely to perceive climate change.

Table 6.2: Logistic regression predicted the influence of socioeconomic and demographic factors on the perceptions of climate change. Significant values are in bold. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Variables	**Coefficient**	**Std. error**	***p*-value**
Gender (Ref: Female)			
Male	2.175	1.292	0.092
Age	-0.046	0.047	0.332
Education (Ref: College/University			
No education	**-3.536***	1.714	0.039
Primary-secondary	-1.806	1.506	0.230
Household size	0.084	0.226	0.710
Agricultural income	-0.262	0.923	0.777
Monthly income (Ref: <17,500 PKR)			
17,500 - 30,000 PKR	1.069	1.135	0.346
>300,000 PKR	2.971	1.706	0.082
Ownership of agricultural land	**2.984***	1.465	0.042
Affected by an extreme event	**7.266** ***	2.063	0.000

6.3.3 Climate change trends in the Lotkuh Valley

To compare perceptions with climate data, trend analysis of climate change indicators based on ERA5-Land for climate change indicators and MODIS for snow cover was conducted which showed a significant trend for five variables (Table 6.3). Frost days (days <0°C) declined with an average reduction of about 12 days over the survey period, whereas summer days (days >20°C) did not show any trend (p-value: 0.039, 0.361, respectively). Several temperature indicators showed significant increases but with some differences between the indicators. Averaged over the whole year, all temperature variables (Tmean, Tmax, Tmin) showed significant increases around 0.7°C over the 50 years from 1970 to 2019 (p-value: 0.012, 0.013, 0.039, respectively).

Seasonal analysis showed no trends for summer, but a very strong trend in winter Tmax with an averaged linear increase of around 1°C from 1970 to 2019 (p-value: 0.046). All other trends, such as yearly precipitation, precipitation intensity, or snow cover, were not significant. Precipitation showed a strong variability with regular differences of more than 100 mm between the years (Figure 6.4). Additionally, strong yearly temperature variations characterize the research area. Generally, all climate change indicators resulted in high year to year variability but only a third resulted in significant trends.

Table 6.3: Seasonal and annual trends of climate parameters for Lotkuh Valley. Trends of temperature and precipitated are calculated using ERA5 (1970-2019) and snow trends from MODIS Snow Product (2001-2019). Significant values are in bold. $*p < 0.05$.

Climate parameters	**Prewhitened Sen's Slope**	***p*-value**
Frost days	**-0.241****	**0.039**
Summer days	0.129	0.361
Summer temperature (mean)	0.006	0.443
Summer temperature (max)	0.013	0.182
Summer temperature (min)	0.002	0.816
Yearly temperature (max)	**0.017****	**0.013**
Yearly temperature (min)	**0.012****	**0.039**
Yearly temperature (mean)	**0.014****	**0.012**
Winter temperature (mean)	0.016	0.274
Winter temperature (max)	**0.021***	**0.046**
Winter temperature (min)	0.011	0.398
Yearly precipitation	-1.427	0.176

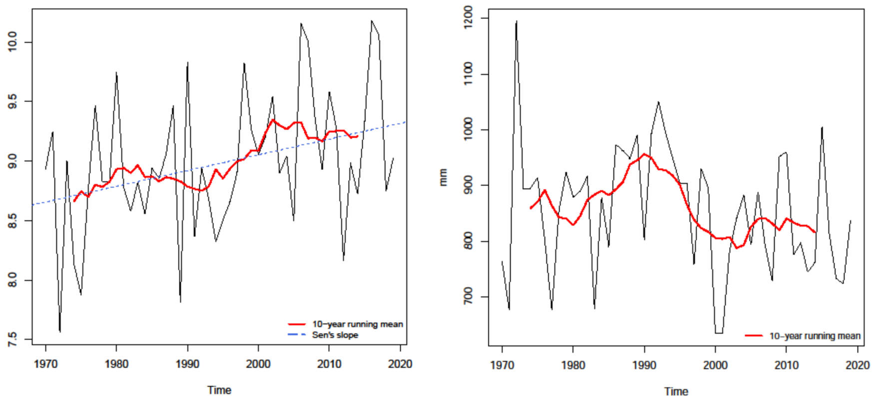


Figure 6.4: Yearly average, 10-year running means, and trends of annual mean temperature (left) and precipitation (right). Only significant linear trend lines are plotted for clarity.

Climate parameters	**Prewhitened Sen's Slope**	***p*-value**
Winter precipitation index	-0.003	0.797
Summer precipitation index	-0.003	0.776
Snow cover (mean)	0.057	0.820

6.3.4 Multi-hazards and their impacts on people's livelihoods

The impact of climate change is also revealed by our results which show that the communities in the Lotkuh Valley face a multitude of natural hazards and associated events (Figure 6.5). A vast majority of households, i.e., 83% (n=321) out of 388 surveyed households reported that they were affected by an extreme event during 2010-2020. Among these events, floods (54%), landslides (33%), and avalanches (31%) are the top three natural hazards affecting people in the Lotkuh Valley. Heavy snowfalls and rainfall events also affected 20% and 11% of surveyed households, respectively. Moreover, water shortages were reported by 6% and drought by a mere 2% of surveyed households. Other than these events, earth-

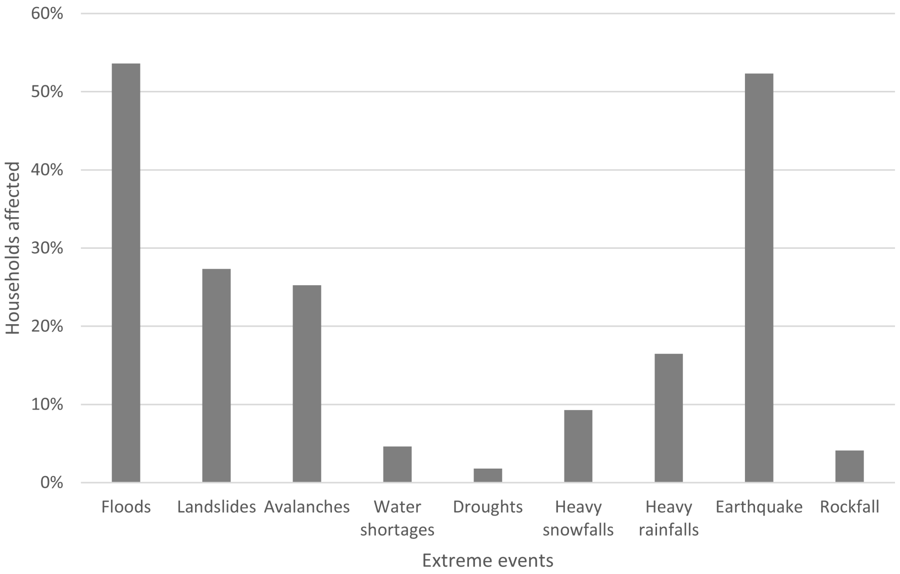


Figure 6.5: Households affected by various types of natural hazards.

quakes are a quite common geological hazard in the whole Hindu Kush region, and they affected 63% of surveyed households in the Lotkuh valley. Lastly, rockfalls were reported by 5% of surveyed households. People mentioned that major earthquakes trigger further natural hazards such as landslides, avalanches, and rockfall in the area. The spatial analysis of the extreme events is presented in Table 6.4. Floods, landslides, and earthquakes had an impact on 12 out of 13 sampled villages. Similarly, avalanches affected 10 villages across the valley. Moreover, heavy snowfall and rainfall events also incurred losses to households in several villages. The multi-hazard phenomenon, where a community is exposed to the risk of more than one hazard type, is common across the villages of Lotkuh Valley. In terms of multi-hazards, all 13 villages were prone to the impacts of at least 3 different types of natural hazards.

Further to this, at least 9 villages have experienced 5 types of hazards. Finally, four villages, namely Roi, Shut, Wakht, and Zhitur have experienced at least 8 types of hazards which show that they are highly vulnerable to the effects of the multi-hazard phenomenon. These multi-hazards further interact with each other and cause compound hazards. The people during the interviews and focus groups revealed that earthquakes followed by heavy precipitation triggered landslides and avalanches thus making

Village	Flood	Landslide	Avalanche	Water shortage	Drought	Heavy snowfall	Heavy rainfall	Earthquake	Rockfall
Gobore	96.2	26.9	76.9			84.6	53.8	76.9	
Khatinj	45.5	100	72.7					63.6	
Madashil		27.3	12.1			9.1	3	21.2	
Parabeg	83.7	57.1	38.8				12.2	77.6	
Parsan	24.1	75.9						6.9	
Roi	100	17.4	21.7	47.8	13	13	65.2	91.3	
Shershal	4	16.7	37.5			4.2			4.2
Shoghore	76.9	3.8						38.5	
Shut	51.9	51.9	3.7	3.8		7.4	29.6	63	
Siyah Arkari	46.7			3.7			4.4	22.2	
Uchugol	23.2	3.6	35.7			5.4		64.3	26.8
Wakht	100	7.1	78.6	21.4	14.3	7.1	35.7	92.9	
Zhitur	100	12	4	8	8	4	52	88	

Table 6.4: Households (%) affected by natural hazards in surveyed villages (n=388).

them more susceptible to the impacts. The multi-hazard phenomenon for Shershal is illustrated by an interview participant below:

> *"There was an avalanche in the village which caused a lot of damage in the village. Even before 2010, there have been losses due to landslides. There was a flash flood in 2015."* (Interviewee, Shershal, 2020)

Communities also perceived flood as a frequent and most impactful natural hazard in our study area. The interviews and focus groups show that the last three major flood events took place in 2010, 2013, and 2015. These flood events caused widespread destruction and damage to the livelihoods of the people in several villages. The geographical distribution of flood impact is shown in Figure 6.6. People also indicated that due to population growth and urbanization, they are expanding houses and community infrastructure to areas prone to floods. Moreover, it was noticed that several of the villages, such as Siyah Arkari, Gobore, Zhitur, Wakht, Roi, and Shoghore, are exposed to flood risk from multiple streams (locally called gols) and rivers. All these factors contribute to the high risk of flood impacts and turn it into a compound hazard in the area. The impressions of catastrophic floods in Roi mentioned by a focus group participant are given below:

> *"There are many witnesses [people affected] that you can find in our area but what happened in 1995 and 2013 was quite surprising. They [floods] affected us badly which we remember very clearly."* (FGD participant, Roi, 2020)

The survey results showed that the extreme events had impacted the lives and livelihoods of the communities in the Lotkuh Valley (Figure 6.7). In terms of loss and injuries to people's lives, avalanches have been deadly (3%) among surveyed households. Moreover, people's homes, which is one of the most at-risk elements, were struck by earthquakes (44%), floods (16%), avalanches (11%), and landslides (10%). In some circumstances when people receive a warning of an event such as a flood they evacuate

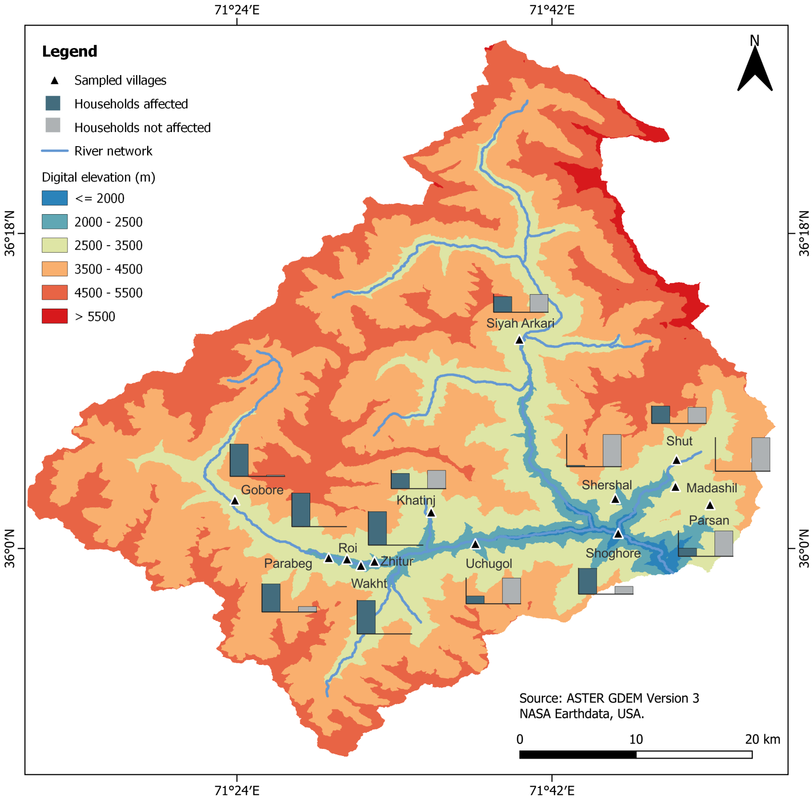
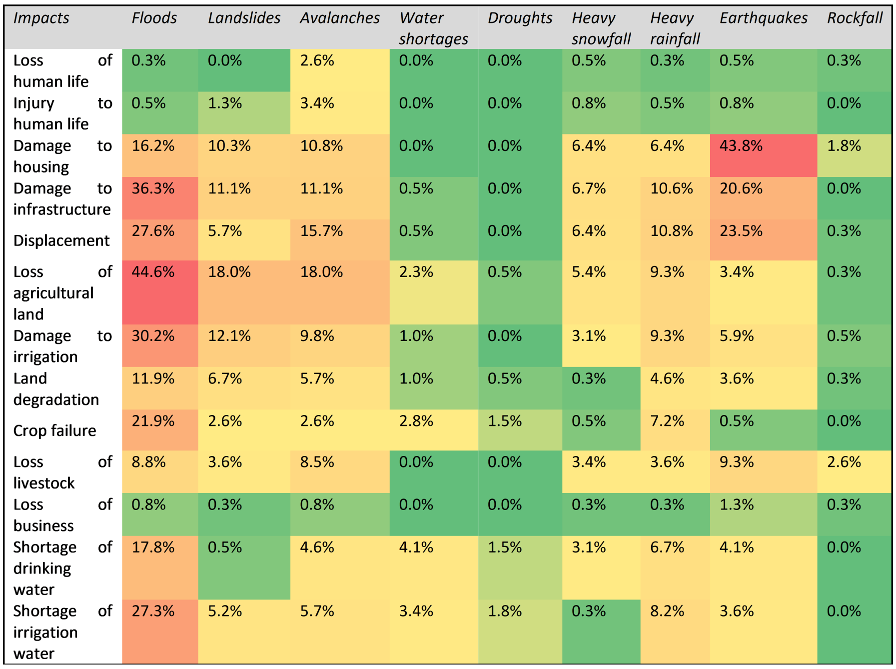


Figure 6.6: Distribution of flood impact in the Lotkuh Valley. Percentage of households affected by floods in the sampled villages.



Impacts	*Floods*	*Landslides*	*Avalanches*	*Water shortages*	*Droughts*	*Heavy snowfall*	*Heavy rainfall*	*Earthquakes*	*Rockfall*
Loss of human life	0.3%	0.0%	2.6%	0.0%	0.0%	0.5%	0.3%	0.5%	0.3%
Injury to human life	0.5%	1.3%	3.4%	0.0%	0.0%	0.8%	0.5%	0.8%	0.0%
Damage to housing	16.2%	10.3%	10.8%	0.0%	0.0%	6.4%	6.4%	43.8%	1.8%
Damage to infrastructure	36.3%	11.1%	11.1%	0.5%	0.0%	6.7%	10.6%	20.6%	0.0%
Displacement	27.6%	5.7%	15.7%	0.5%	0.0%	6.4%	10.8%	23.5%	0.3%
Loss of agricultural land	44.6%	18.0%	18.0%	2.3%	0.5%	5.4%	9.3%	3.4%	0.3%
Damage to irrigation	30.2%	12.1%	9.8%	1.0%	0.0%	3.1%	9.3%	5.9%	0.5%
Land degradation	11.9%	6.7%	5.7%	1.0%	0.5%	0.3%	4.6%	3.6%	0.3%
Crop failure	21.9%	2.6%	2.6%	2.8%	1.5%	0.5%	7.2%	0.5%	0.0%
Loss of livestock	8.8%	3.6%	8.5%	0.0%	0.0%	3.4%	3.6%	9.3%	2.6%
Loss of business	0.8%	0.3%	0.8%	0.0%	0.0%	0.3%	0.3%	1.3%	0.3%
Shortage of drinking water	17.8%	0.5%	4.6%	4.1%	1.5%	3.1%	6.7%	4.1%	0.0%
Shortage of irrigation water	27.3%	5.2%	5.7%	3.4%	1.8%	0.3%	8.2%	3.6%	0.0%

Figure 6.7: Impacts of extreme events on the livelihoods of surveyed households (n=388).

to safe places while in other situations they are displaced after the event strikes and damages their homes. Floods (28%), earthquakes (23%), and avalanches (16%) are the major events that triggered the ex-ante or ex-post displacement of surveyed households. The livelihoods of the communities in the area depend on agriculture and livestock farming which are prone to the adverse impacts of natural hazards. Land, an important and scarce resource for mountain communities, is affected by either its erosion or degradation caused by extreme events. Floods cause the loss of fertile farmland (45%) which mostly lies in the floodplain and in proximity to rivers and streams. Similarly, floods (12%), particularly flash floods, bring debris that is deposited in the farmland resulting in its degradation. A focus group participant highlighted the impact of a flood in 2018 in the following:

> *"This catastrophe [flood in 2018] always had a bad impact on our crops but we can't do anything we just wait and watch. Occasionally, we went to cities for employment that year."*

> (FGD participant, Gobore, 2020)

Landslides (18%) and avalanches (18%) also contribute to the loss of agricultural land. Similarly, they also cause land degradation. All these three natural hazards, floods (30%), landslides (12%), and avalanches (9%), severely affect the irrigation channels in the valley. When the households were further asked about the shortages of irrigation water, floods (27%), heavy rainfalls (8%), avalanches (6%), and landslides (5%) are the events that caused them. The impacts on community infrastructure are echoed by an interview participant in the following:

> *"All the irrigation channels are washed away then these are reconstructed. Sometimes crops are destroyed because of this, then bridges are washed away, roads are washed away. These difficulties are always faced [by us]."* (Interviewee, Siyah Arkari, 2020))

The communities mentioned that the restoration and rehabilitation of the affected irrigation channels is a difficult task that has negative consequences not only for agricultural production but as additional economic and human strain. Crop failure is also reported by the surveyed households mainly caused by floods (22%). Furthermore, floods, earthquakes, and avalanches have been catastrophic for livestock (9%), which is an important part of the livelihoods of mountain people. Finally, floods (36%) and earthquakes (21%) also inflicted damage to the community infrastructure in the area.

6.3.5 Detection of floods using Landsat time series

To show the spatiotemporal aspects of flood events identified through interviews and focus groups, we used the BFAST method to detect floods in Siyah Arkari, Roi, Gobor, Parabeg, Shoghore, and Zhitur. To showcase an example, we present the results of the 2015 floods (Figure 6.8) in Shoghore which were strongly mentioned by local people. Several spells of flooding were detected from February to September 2015, but major

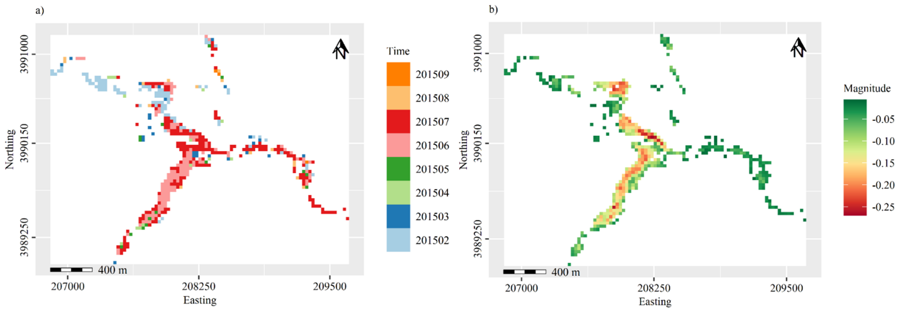


Figure 6.8: BFAST detected the 2015 flood event in Shoghore: A) shows the timing of the flooding; B) the magnitude of change in MSAVI.

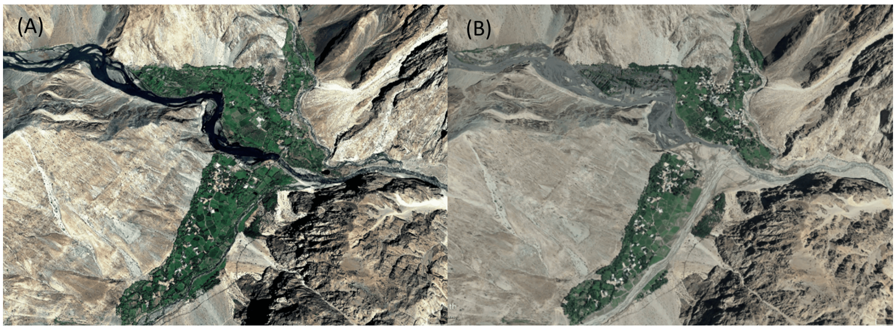


Figure 6.9: Pre and post-flood imagery from Google Earth: A) Image from 13 Aug 2009, which shows the pre-flood situation in Shoghore; B) Image from 15 August 2017, showing the impact of flood along the riverbanks.

events are concentrated during June-July (Fig. 8A). Shoghore experienced floods from three sides. The magnitude of the flood event showed that the negative abrupt change in vegetation ranged between 0 and -0.2 (Fig. 8B). The more the negative change in magnitude the more the loss in vegetation. Post-flood Google Earth image shows the land degradation phenomenon by the flooding in Shoghore compared to the pre-flood image in which the croplands are flourishing (Figure 6.9).

6.3.6 Integrating perceptions with biophysical data

Using the research framework proposed in the study, we integrate perceptions and analysis of biophysical data on climate change perceptions and their impacts on livelihoods. Most of the respondents perceived a change in temperature (96%) and precipitation (92%) in the Lotkuh Valley. The trend analysis also confirms that the annual temperatures (mean, min, and max) are increasing, while annual precipitation trends are not significant. Similarly, there is a divergence on the snow where perceptions indicate it is decreasing while MODIS data show no trend. In terms of changes in seasonal patterns, people perceived summer duration as increasing (54%) and winter as decreasing (45%). In comparison, climate data shows that summer days have no trend while frost days are in decline.

The analysis of perceptions indicated that floods are the most important hazard in the Lotkuh Valley. It has affected most of the sampled villages in our area. The perceptions highlighted the adverse impacts of the flood on their livelihoods particularly the loss of agricultural land (46%), disruption of irrigation network (30%) and other infrastructure (36%), displacement (28%), and damage to houses (16%) among others. BFAST results (Fig. 8) confirmed these impacts and provide a visual illustration of the flood extent and its impact as shown in the example from Shoghore. The analysis of MSAVI data adds more vital information on the different flood spells in 2015 and the corresponding area affected by them, as also the severity of the events in terms of vegetation loss.

6.4 Discussion

This is the first study that compared the perceptions of climate change and its impacts with quantitative climate data and remote sensing results in the Eastern Hindu Kush region. Our results indicated that most of the respondents perceived that the Lotkuh Valley experienced changes in temperature and precipitation. This is in line with previous studies conducted in the neighboring Rakaposhi valley of Gilgit-Baltistan, which also reported over 90% of respondents perceived changes in temperature and precipitation (Bhatta et al., 2019). Moreover, people noticed an increase in local temperature in the Lotkuh Valley. Other studies in Indus and other basins reported similar perceptions of temperature increase (Hussain et al., 2016; Joshi et al., 2013), but in contrast to decreasing temperatures perceived in Karakoram (Gioli et al., 2014).

As far as the changes in precipitation are concerned, people perceived an increase in overall rainfall but also reported differences with respect to seasonal patterns. On the other hand, people noted a decrease in snow throughout the Lotkuh Valley which is consistent with perceptions in Pamirs (Haag et al., 2021) and Booni in Upper Chitral (Ajani & van der Geest, 2021) but in contrast to heavy snowfall noted in Gilgit-Baltistan (Joshi et al., 2013). People also perceived seasonal climate changes in the area such as the shorter winters and the longer summers, similar to the patterns noted in Gilgit-Baltistan (Joshi et al., 2013). People also mentioned a shift in the rainfall maximum from spring to summer in recent years. Summer rainfall, which they associated with the monsoon, is new to the Lotkuh valley according to the survey participants. Monsoon rains adversely affect the standing crops that are ready for harvest. Farmers find rainfall in spring more beneficial as it serves irrigation needs. Overall, the upward trend in temperature and rainfall variability perceived by communities is in line with perceptions reported from other basins in the HKH (Dilshad et al., 2019; Joshi et al., 2013). The perceived increase in annual precipitation and increase in summer rainfall is consistent with perceptions in Hunza and Yasin valleys in the Giglit-Baltistan region (Gioli et al., 2014). However, perceptions of increasing rainfall differed from decreasing rainfall noted in Koshi basin (Hussain et al., 2016) and Gilgit-Baltistan (Joshi et al., 2013), and increasing summer temperature in our study area was not noted in the Pamirs (Haag et al., 2021). The differences in perceptions from our study with other studies could be due to the time period, as noted in Spies(Spies, 2020) which used 30-40 years, Gioli et al. (2014) with 10 and 20 years, and Hussain et al. (2016) with 10 years.

In terms of the factors that shape perceptions of climate change, our regression results showed that those with no formal education compared to college or university graduates are less likely to perceive climate change. Possession of agricultural land is also associated with perceiving climate change, probably farmers' experience of noticing changes in seasonal patterns and effects of temperature and precipitation on the crops. Education as a determinant of climate change perceptions is also noted in Ghana (Guodaar et al., 2021) and Qilian Mountains (Xie et al., 2022). Furthermore, those who have been affected by an extreme event in the past are more likely to perceive climate change. This is due to the awareness and trainings received from NGOs and Aga Khan Development Network (AKDN) in the aftermath of floods in the area, which is similar to the increased climate change perceptions of those affected by the Attabad disaster in Hunza (Gioli et al., 2014). The analysis of ERA5 data shows that yearly temperature trends (annual mean temperature, annual minimum, and annual maximum) have increased in our study area from 1970 to 2019. Seasonally, winter was characterized by stronger changes with warmer Tmax and a reduction in frost days, whereas summer did not show a temperature trend. It is important to state that the respective region may also be influenced by some of the climatic causes of the so-called Karakoram Anomaly, a stable period in some glaciers in the region, that is associated with decreasing summer Tmax from 1970 until 2010 among other factors (Ougahi et al., 2022). The presented climate analysis is also similar to other research using station data, stating no change in summer temperatures but a significant increase in winter (S. Ahmad et al., 2021). Other studies even state the cooling of annual temperatures between 2000 and 2013 (S. Ahmad et al., 2020), although the respective period may be too short for meaningful trend calculations.

In addition, no trends were found for precipitation, which is similar to existing research from the region (S. Ahmad et al., 2020; S. Ahmad et al., 2021). Remote sensing data did not reveal any significant trends in snow cover, whereas other regional studies also do not present conclusive trends, as some state increase in snow cover or static conditions, or different results from villages in close proximity to each other (S. Ahmad et al., 2020; S. Ahmad et al., 2021). In summary, our analysis matches very well with the station data and existing research, bringing confidence to the ERA5 trends. Therefore, the quantitative analysis, which is backed by other empirical studies, differs from perceived climate change in several aspects.

Changes in temperature and precipitation have implications for local livelihoods. Rise in temperature and erratic rainfall patterns affect the agricultural yield through shifts in harvesting period, crop failures, and poor crop production. Moreover, hot summers and changes in the onset of seasons also make crops susceptible to new pests and diseases. In addition, the decrease in snow cover has implications for water availability in some areas which depend on the snowmelt water for their croplands. All these factors induced by climate change cause lower income from agriculture. Similar perceptions of the impact of climate change on crop productivity are reported in previous research in the region (Ajani & van der Geest, 2021; Bhatta et al., 2019).

Our analysis shows that the Lotkuh Valley is highly susceptible to multi-hazards which trigger connecting and compound extreme events. It was noticed that 12 out of 13 surveyed villages are prone to at least 3 hazards (i.e., floods, earthquakes, and landslides). Moreover, the Hindu Kush region faces frequent earthquakes which not only affect local people but exacerbate the occurrence and impact of landslides and avalanches. Heavy rainfall and snowfalls also result in landslides and avalanches in the area. Flooding is the most important extreme event in the area which affected most of the surveyed households. The villages located next to the major tributaries of the Lotkuh River are prone to riverine floods while flash floods caused by heavy and intense rains are affected by flash floods. Spatial analysis of flood events shows that all surveyed villages except Madashil were affected. Gobore, Parabeg, Roi, Wakht, Zhitur, and Shoghore are highly vulnerable to these events. Our finding that flood is the most frequent and impactful hazard also matches with other research studies in HKH (Ajani & van der Geest, 2021; Bhatta et al., 2019; Dilshad et al., 2019; Hussain et al., 2016).

Analysis of Landsat data using BFAST also provides information on the spatiotemporal aspects of flood events. It detected the large areas of interconnected pixels validated through Google Earth imagery and local information. BFAST results confirmed the timing and location of the

2015 flood in Shoghore and also provided information on the extent and severity of the event. The approach is more suitable for flood detection than landslides or other hazards which have less spatial area (Khan et al., 2022). Our findings on the impact of extreme events match with other studies carried out in the region that highlight similar impacts of hazards on people's livelihoods (Ajani & van der Geest, 2021). The awareness about multi-hazards and their interactions in specific locations should provide important input to policymakers so that different risk reduction measures are synergistic and not counter-adaptive to each other (Rusk et al., 2022).

Our study complements the previous research (Rusk et al., 2022) on multi-hazards assessment in HKH by gathering peoples' perceptions of multi-hazards, their cascading effects, and compound hazards. The most important element at risk is their lives and avalanches have caused relatively more loss of life and injuries to the people compared to other hazards. Houses are also severely affected by earthquakes, floods, avalanches, and landslides. The severity and potential risk to people's lives and livestock also trigger ex-ante and ex-post displacement. Another critical part of their livelihoods that is vulnerable to extreme events is the agricultural land and the irrigation networks running along scree slopes and talus cones (Nüsser, 2001). Floods have the most devastating impact on the loss of agricultural land and its degradation. The importance of land resources and their vulnerability to floods is also highlighted in previous research in the HKH (Ajani & van der Geest, 2021).

The study demonstrated that our proposed framework is not only capable of integrating climate change perceptions (including extreme events) with analysis of biophysical data, but also shows several discrepancies between them. The contrasting results between perceptions and climate trends could be due to the perceptions being more influenced by recent flood events resulting in increased awareness provided by external actors, as also noted in Karakoram (Gioli et al., 2014) and farmers' experience with the shortage of irrigation water which they attribute to decrease in snow and rainfall variability (Spies, 2020). The erratic summer rains, particularly during monsoon disrupt the harvest and cause low yield thus also influencing their perception of an increase in rainfall. Moreover, it will increasingly become difficult for farmers to accurately perceive the long-term changes in rainfalls with increasing variability in its patterns (Guodaar et al., 2021). Nevertheless, our framework provides a useful and practical approach to integrating results by combining different methods with different disciplinary origins. The framework also shows the relationship between livelihoods and climate change in the mountain-specific context of the Eastern Hindu Kush.

People's awareness and strong perceptions of climate change in Lotkuh Valley are helpful when it comes to climate change adaptation. Perceptions and experiences of local communities will potentially result in their willingness to respond to the challenges associated with climate change and extreme events at the local level (Abid et al., 2019). These perceptions would potentially engender their participation in the robust implementation of adaptive and risk-reduction strategies, and also increase their mobilization to invest in long-term solutions (Guodaar et al., 2021). Our results will inform future interventions to address the implications of climate change on local livelihoods, more specifically to be able to account for warming seasons and connected and compound extreme events.

6.5 Conclusion

This paper integrated climate change perceptions and impacts of extreme events with the analysis of climate and vegetation data in the Lotkuh Valley of Chitral, north Pakistan. We employed an interdisciplinary approach comprising methods from social science (interviews, focus groups, household survey) and physical science (remote sensing, climate data analysis) to gain holistic and integrated perspectives on climate change in our study area.

The study shows that most people perceived changes in temperature and precipitation and seasonal patterns. Climate change affects their livelihoods (agriculture, livestock) which heavily depend on local natural resources. The warming of seasons and changes in seasonal patterns adversely affect crop productivity. Changes in rainfall patterns such as the increase in monsoon rains disrupt the standing crops. People also perceived a decrease in snow and attributed the shortage of water to this decrease. The analysis of climate trends show provides a divergent view of precipitation and snow as the trends are not significant. However, the rising temperature trends and decrease in frost days confirmed community perceptions of warming and a decrease in the length of the winter season. The study also showed that the local perceptions of climate change are influenced by education, ownership of agricultural land, and experience of extreme events. The insights provided by this study on perceived climate change and its impacts on agricultural production, livestock, and land resources are useful for policymakers to formulate adaptation strategies. Furthermore, integrating local perceptions of climate change with the analysis of climate trends offers a solution to potential problems associated with climate data, such as the lack of weather stations in high mountains and coarse models. This approach provides a more nuanced understanding of climate change and its impacts at the local level.

Our findings showed that most of the villages are prone to multi-hazards. The presence of several hazards causes connecting and compound extreme events with adverse impacts on livelihoods. Floods, landslides, avalanches, and earthquakes are the frequent hazards that cause loss of human lives, as well as displacement, land degradation, crop failures, loss of livestock, and disruption of infrastructure. Floods are the most impactful hazard in the area. Analysis of Landsat-derived MSAVI time series with the BFAST method confirmed the flood events in different villages mentioned by local people, as shown in the case of the 2015 flooding in Shoghore. Government and non-government actors must take into account the compound nature of natural hazards, which often lead to interconnected and severe events, impacting local livelihoods in various ways.

Finally, this study fills the important empirical research gap in the Eastern Hindu Kush region on climate change and its impacts on mountain livelihoods. Our research framework for the integration of climate change perceptions and biophysical data provides a useful approach for future integration studies on climate change.

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7. Manuscript II: Detecting Abrupt Change in Land Cover in the Eastern Hindu Kush Region Using Landsat Time Series (1988-2020)

Outline

Bibliographic Information

Khan, S. A., Vanselow, K.A., Sass, O., & Samimi, C. (2022). Detecting abrupt change in land cover in the eastern Hindu Kush region using Landsat time series (1988-2020). Journal of Mountain Science, 19(6), 1699-1716. `https://doi.org/10.1007/s11629-021-7297-y`

Article Adaptation

The contents of the original version had to be slightly modified for its inclusion in this dissertation, including the numeration of sections, figures, tables, and equations had to be adjusted. The published version of this article can be found at `https://doi.org/10.1007/s11629-021-7297-y`.

Abstract

Land cover change in the semi-arid environment of the eastern Hindu Kush region is driven by anthropogenic activities and environmental change impacts. Natural hazards, such as floods presumably influenced by climatic change, cause abrupt change of land cover. So far, little research has been conducted to investigate the spatiotemporal aspects of this abrupt change in the valleys. In order to explore the abrupt change in land cover and floods as its possible drivers in the eastern Hindu Kush, a semi-arid mountain region characterized by complex terrain, vegetation variation, and precipitation seasonality, we analyzed long-term Landsat image time series from 1988 to 2020 using Breaks For Additive Seasonal and Trend (BFAST). Overall, BFAST effectively detected abrupt change by using Landsat-derived Modified Soil Adjusted Vegetation Index (MSAVI). The results of our study indicate that approximately 95% of the study area experienced at least one abrupt change during 1988-2020. The years 1991, 1995, 1998, 2007, and 2016 were detected as the peak years, with the peaks occurring in different seasons. The annual trend of abrupt change is decreasing for the study area. The seasonality of abrupt change at the catchment level shows an increasing trend in the spring season for the southern catchments of Panjkora and Swat. The spatial distribution patterns show that abrupt change is primarily concentrated in the floodplains indicating that flooding is the primary driver of the land cover change in the region. We also demonstrated the accurate detection of past flood events (2015) based on the two case examples of Ayun, Rumbur, and Kalash valleys. The detection of the flood events was verified by fieldwork and historical high-resolution Google Earth imagery. Finally, our study provides an example of applying Landsat time series in a dry mountain region to detect abrupt changes in land cover and analyze impact of natural hazards such as floods.

7.1 Introduction

The Hindu Kush-Karakoram-Himalaya (HKH) is a geo-ecologically important mountain region as it provides ecosystem services to 240 million people living in this area (Wester et al. 2019). HKH region is prone to several natural hazards (Rusk et al., 2022). It is highly susceptible to geological hazards such as earthquakes, landslides, rockfalls, and erosion, mainly because it is a relatively young geological formation (Hewitt, 1992; Kamp et al., 2004; Nibanupudi & Shaw, 2015). In addition to geological threats, hydrometeorological hazards pose a significant risk to the people living in the HKH region. Floods constitute a considerable danger throughout the entire area area (Elalem & Pal, 2015; Tsering et al., 2021). Riverine and flash floods are common recurring disasters (Khan et al., 2013; Nibanupudi & Shaw, 2015; Tsering et al., 2021). In particular, on the slopes of the highly elevated upper catchment areas of rivers, sudden and intense rainfall causes flash floods (Atta-ur-Rahman & Khan, 2011; Lu et al., 2022). Such events are also supplemented by glacial melting and heavy snowfall, resulting in flash floods in the downstream valleys. The sudden bursting of glacial lakes also causes outburst floods in the valleys (Allen et al., 2016; Ashraf et al., 2021; Sati, 2022; Veh et al., 2018). The presence of many glacial lakes in the mountainous region increases the flood risk for the settlements in the floodplains (Ashraf et al., 2021; Ashraf et al., 2014; Rehman et al., 2014). Moreover, riverine flood events also destroy farmlands, irrigation infrastructure, housing, roads, vegetation, and livestock (Ashraf et al., 2021; Atta-ur-Rahman & Khan, 2011, 2013; Hewitt & Mehta, 2012; Khalid et al., 2021; Nüsser, 2001). The impacts of natural hazards further exacerbate societal problems, including the out-migration from mountain areas of HKH (Gioli et al., 2014; Maharjan et al., 2021; Rusk et al., 2022).

Several studies have investigated the impacts of flood events in the HKH region (Ashraf et al., 2012; Ashraf et al., 2014; Sati, 2022; Shan et al., 2021; Veh et al., 2018). Damage assessments were carried out using remote sensing data and techniques. For instance, the impacts of the 2010 floods in Punjab and 2011 floods in Sindh provinces of Pakistan were analyzed (Gaurav et al., 2011; M. Haq et al., 2012). In addition, research has been conducted on spatiotemporal changes in forest cover in the HKH region (F. Haq et al., 2018; Ullah et al., 2016; Zeb, 2019). However, there is a lack of research on the long-term spatiotemporal analysis of abrupt change in land cover in the valleys. Abrupt changes in land cover are generally caused by anthropogenic activity (e.g., deforestation and urbanization etc.) and natural processes such as floods and landslides (Chen et al., 2014; Xu et al., 2020). These abrupt changes can be driven by many factors, including past events' impact (Chen et al., 2014; Fang et al., 2018; Watts & Laffan, 2014). The impact and timing can vary in different catchments for different seasons. Therefore, both seasonal and catchment level analyses of abrupt changes are crucial to understand land cover change dynamics in the region.

Remote sensing methods provide an ample opportunity to detect land cover changes in remote, complex mountain regions and on a large scale (Anderson et al., 2020; Geng et al., 2019; Mishra & Chaudhuri, 2015) and have been widely used in land cover change detection (Brown et al., 2012; Brown et al., 2006; Running et al., 1995; Tian et al., 2016). The Landsat program offers satellite imagery with a long historical record and is very suitable to detect past changes in the land cover (Campbell, 2011; Young et al., 2017; Zhu, 2017, 2019). In particular, time series analysis of vegetation indices derived from Landsat sensors has been extensively applied to analyze changes in land cover and their causes (Franklin et al., 2015; Panday & Ghimire, 2012; Zhu, 2017, 2019).

Recent literature shows that Landsat time series have been used in studies on glacier dynamics, detecting glacial lakes, their expansion, and associated floods in different mountain regions such as HKH, Central Asia, and European Alps (Huang et al., 2018; Ma et al., 2021; Veh et al., 2018; S. Y. Yan et al., 2018; Zheng et al., 2019). In addition, changes in a forest in wetland areas of China were investigated, and flood impact on Swiss floodplains was also analyzed (Milani et al., 2020; Wu et al., 2020). However, we found that no studies are using Landsat time series to analyze abrupt changes in a dry mountain region, such as the eastern Hindu

Kush. Our study aims to fill this research gap by using the Landsat time series (1988-2020) to detect abrupt change in land cover in dry mountain regions, like the eastern Hindu Kush.

The main objective of this study was to investigate the abrupt changes in land cover in the eastern Hindu Kush and then compare their occurrence and impacts for the different catchments. This research attempts to answer the following specific aims: (1) to detect and map abrupt changes, including peak years, in the trend component of the Landsat time series; (2) to analyze detected abrupt changes at the catchment level; (3) to extract past flood events in the valleys and map their timing and magnitude of change in the land cover. As such, our study represents a prime example for analyzing land cover change using raster time series analyses in a dry mountain area that could also be applied to similar regions.

7.2 Study Area

The eastern Hindu Kush region is surrounded by the Karakoram and Himalayan ranges in the east and southeast and the Pamir mountains in the north and northwest. Our study area is situated in the north of Khyber Pakhtunkhwa province and western part of Gilgit- Baltistan in Pakistan, and eastern parts of Nuristan and Badakhshan provinces of Afghanistan, between 35°20’24” and 36°43’48” N, and 71°19’12” and 72°59’24” E. It has an extent of approximately 22,000 km2 (Figure 7.1). The north of the study area is part of the Amu Darya basin with Wakhan and Warduj catchments. The central part drains into the Chitral catchment, while the Basghal catchment lies on the south-western side. The south of the study area has Panjkora, Swat, and Kandia catchments, while the Gilgit catchment is in the east.

Chitral River (also called Kunar) is the main river in the eastern Hindu Kush. In addition to Chitral, other rivers in the study area are Panjkora, Swat, Gilgit, Kandia, Wakhan, Warduj, and Bashgal. All these rivers are tributaries of the Upper Indus River Basin except the Warduj and Wakhan rivers which are part of the Amu Darya in Afghanistan and

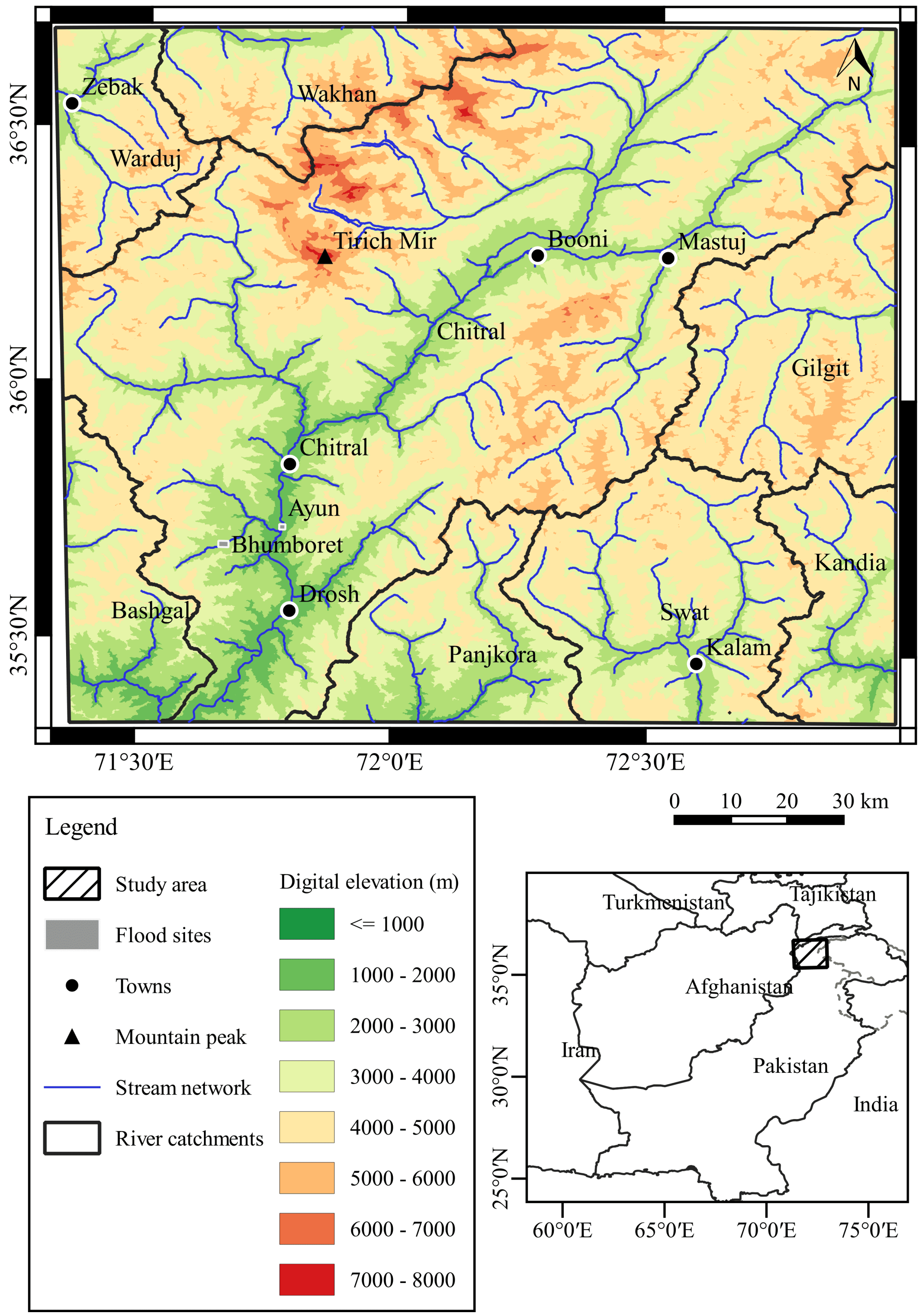


Figure 7.1: Overview of the study area in the eastern Hindu Kush mountain region and catchments of tributary rivers of the Upper Indus basin and Amu Darya. (Data source: ASTER GDEM Version 3 NASA Earthdata, USA)

Central Asia. Tirich Mir (7,708 m), the tallest peak in the Hindu Kush range, is located among other mountains and glaciers in the study area. Most of the settlements are along the riverbanks of the Chitral River and other tributaries. The majority of the population is rural, while Chitral town (35°51'17.19" N, 71°47'21.74" E), with about 49,000 inhabitants, is the largest urban settlement located in the southwest of our study area (Fig. 1). Chitral weather station recorded an annual mean temperature of 16.1°C and total annual precipitation of 405 mm from 1970 to 2019 (PMD, 2020). The north and northwest part of the study area receives less rain with a peak in winter and spring, while the south and south-eastern side receive more monsoon rains in summer (Nüsser & Dickoré, 2002). Forests are located in the southern part, whereas central and the northern Chitral is largely treeless (Nüsser & Dickoré, 2002; Zeb, 2019).

7.3 Data and Methods

7.3.1 Data

Landsat data

We choose the Modified Soil Adjusted Vegetation Index (MSAVI) due to its strength to minimize soil background effects caused by the arid and semi-arid conditions, sparse vegetation, and the existence of bare soils in several valleys and surrounding mountains in our study area (Qi et al., 1994). The MSAVI is derived from the reflectance in the near-infrared (NIR) and red bands and is denoted by the following equation:

$$MSAVI = \frac{\left(2 \times NIR + 1 - \sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - RED)}\right)}{2}$$

We acquired MSAVI data derived from 811 images of the sensors Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) for Path 151 and Row 35 (World Reference System-2) for the years 1988 to 2020 (Table 7.1). We selected a full-season archive of images from 1988 to

2020 without applying any seasonal or time-specific filters. The MSAVI data is processed to Level-2 Surface Reflectance data, which means it has undergone radiometric, geometric, and atmospheric corrections by USGS (U.S. Geological Survey, 2015). This data comes with a spatial resolution of 30 m and a temporal resolution of 16 days. It was accessed from the United States Geological Survey's (USGS) Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) platform (https://espa.cr.usgs.gov/).

Table 7.1: Landsat images (1988-2020).

Years	Number of images per Landsat sensor			
	L5 TM	L7 ETM+	L8 OLI	Sum
1988-2000	184	18	--	202
2001-2010	67	143	--	210
2011-2020	16	214	169	399
Total images	267	375	169	811

Note: L, Landsat; TM, Thematic Mapper; ETM+, Enhanced Thematic Mapper Plus; OLI, Operational Land Image; --, not applicable.

Digital elevation model

To derive the river network and catchments in our study area, we used the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 with a spatial resolution of 30 m. It was downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/).

Validation data

To validate the results of flood detection in this study, we gathered data for selected events through fieldwork in the Lower Chitral district in August 2020. This entailed a review of information on these events in disaster reports of local organizations and government (PDMA, 2015; Shah, 2015, 2016). The fieldwork also included visiting Ayun (35°43’29.38” N, 71°46’33.82 E”) which was hit by a riverine flood in 2015, and Bhumboret (35°41’13.88” N, 71°39’ 55.13” E) affected by a flash flood in the same year. We took photographs of the areas impacted by 2015 floods and gathered information from local people through unstructured interviews on the timing and location of these flood events. Furthermore, high-resolution historical imagery was accessed from Google Earth and geo-referenced.

7.3.2 Data pre-processing

Data pre-processing steps are illustrated in the flowchart (Figure 7.2). The Landsat-derived MSAVI images were cropped for the study area, and clouds and cloud shadows were removed using the quality assessment band provided by USGS. Sinks in the DEM were filled, and the river network was generated using Strahler order. Since natural hazards (land erosion, debris flows, etc.) triggered by flood events are concentrated in the valleys along the streams, high slopes, glaciers, and areas remote from streams were masked out using buffers of 250 – 1000 m width along the river network.

7.3.3 Elbow criterion test

Another important consideration before time series analysis was the minimum number of valid observations per pixel. The history of sparse observations by the Landsat program in the late 1980s and 1990s and the persistence of clouds and cloud shadows affected the number of valid observations. Pixels with few valid observations may lead to the detection of false breakpoints. To determine an appropriate threshold of minimum valid observations, we carried out the Elbow criterion test by setting all pixel values to NA if the number of valid observations is less than this threshold (Ketchen & Shook, 1996). We applied this test on seven tiles (out of 100) in our study area with a range of thresholds between 0 and

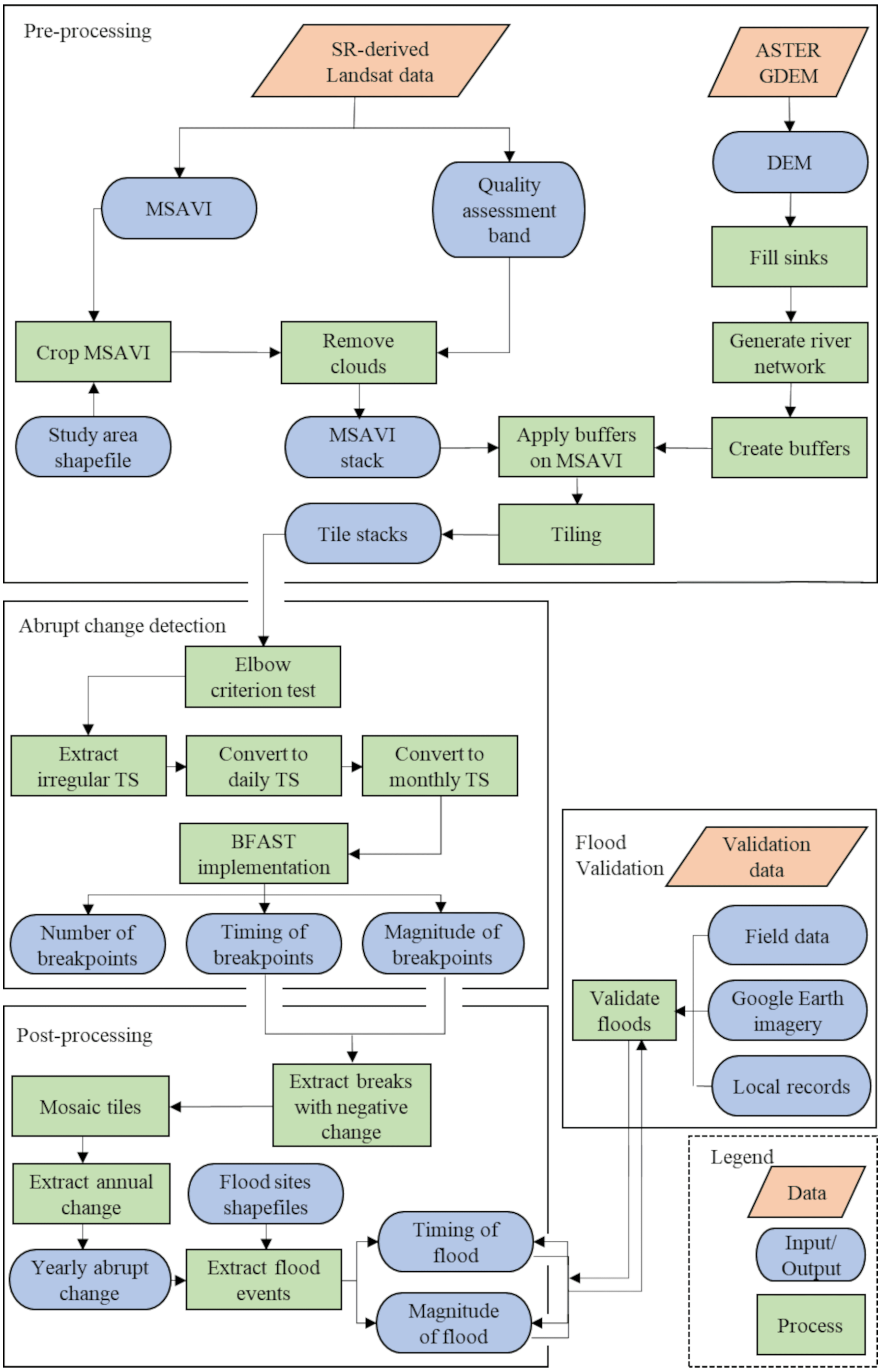


Figure 7.2: Flowchart of the various processing steps undertaken in this study. SR, surface reflectance; ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; GDEM, Global Digital Elevation Model; MSAVI, Modified Soil Adjusted Vegetation Index; DEM, digital elevation model; TS, time series; BFAST, Breaks for Additive Season and Trend.

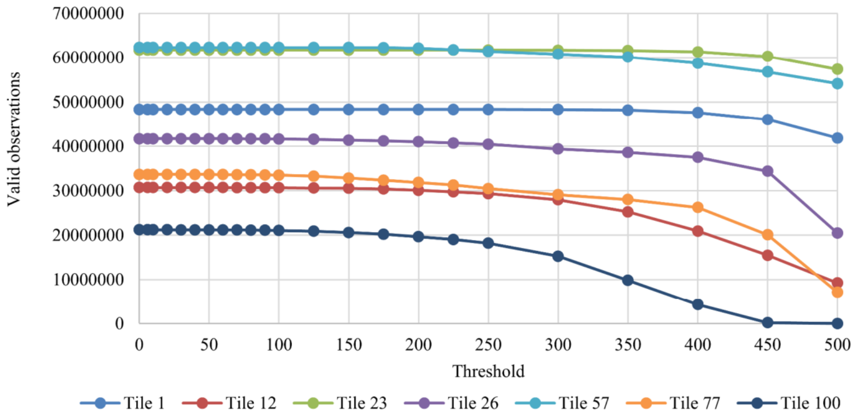


Figure 7.3: Elbow criterion test used to determine minimum valid observation for a pixel. The plot shows a reduction of valid observations (y-axis) for each tile, with an increasing threshold (x-axis).

500. We noticed that valid observations up to a threshold of 200 are stable across the tiles but reduce significantly if the threshold is increased (Figure 7.3). We assume that a minimum of 200 valid observations in the time series is sufficient to detect valid breakpoints for a pixel. All pixels with less than 200 observations are turned to NA (non-applicable) and hence excluded from the breakpoint detection.

7.3.4 Abrupt change detection with BFAST

We used BFAST (Breaks for Additive Season and Trend) for time series analysis of Landsat data from 1988 to 2020 in our study region in the eastern Hindu Kush. BFAST detects abrupt changes on top of seasonal variations and possible trends (Verbesselt et al., 2010; Watts & Laffan, 2014). It is robust against noise and is not influenced by the changes in the seasonal component of the time series (Verbesselt et al. 2010). BFAST has been used to detect abrupt and long-term changes in areas such as deforestation, vegetation, land use, land cover changes, and lake monitoring (Geng et al., 2019; Gholamnia et al., 2019; Lambert et al., 2013; Wu et al., 2020). It has also been applied to detect vegetation changes for selected pixels affected by flood events (Watts & Laffan, 2014). However, BFAST has not been used to detect and map abrupt land cover changes in arid and semiarid environments like the eastern Hindu Kush. This high mountain region has a complex terrain, varying vegetation cover, and strong seasonality of the precipitation (Ahmad et al., 2018; Nüsser & Dickoré, 2002). In addition, the remote sensing imagery of the area contains noise due to persistent cloud cover, especially in the winters. In such conditions, BFAST can be a suitable method because of the aforementioned robustness to noise and strong seasonal amplitudes.

BFAST decomposes a time series into three components: trend, seasonal, and the remainder (or noise) and does not require any historical period or the definition of a trajectory (i.e., a presumption on the expected trend of the data) (Verbesselt et al., 2010). The following equation represents the general model:

$$Y_t = T_t + S_t + e_t \ (t = 1, \ldots, n)$$

where Y_t is the observed data at time t, T_t is the trend component, S_t is the seasonal component, e_t is the noise or remainder component and n is the total number of observations in the time series. The remainder component contains the remaining variation in the data beyond the seasonal and trend components (Verbesselt et al., 2010).

BFAST uses an additive decomposition model which iteratively fits a piecewise linear function with breakpoints $t_1^*, \ldots,\ t_m^*$ and defined $t_0^* = 0$, therefore the trend component can be expressed as:

$$T_t = \alpha_j + \beta_j t$$

where $j = 1, \ldots, m$ and $t_{j-1}^* < t \leq t_j^*$. The magnitude and direction of the abrupt change at a breakpoint is derived using the intercept α_j and slope β_j of consecutive linear models by calculating the difference between T_t at t_{j-1}^* and t_j^*, as expressed below:

$$Magnitude = (\alpha_{j-1} - \alpha_j) + (\beta_{j-1} - \beta_j)\, t$$

BFAST also uses the piecewise linear seasonal model on a seasonal dummy variable to fit the seasonal component (Verbesselt et al., 2010). The timing of breakpoints detected in the seasonal component can differ from those detected in the trend component (Verbesselt et al., 2010). If the seasonal breakpoints are $t_1^{\#}, \ldots,\ t_p^{\#}$, and $t_0^{\#} = 0$, then for $t_{j-1}^{\#} < t \leq t_j^{\#}$, the seasonal component is expressed by following equation:

$$S_t = \begin{cases} \gamma_{\ ij} - \sum_{i=1}^{s-1} \gamma_{ij} \end{cases}$$

$$if\ time\ t\ is\ in\ season\ i, \quad i = 1, \ldots, s-1; if\ time\ t\ is\ in\ season\ 0$$

where S and γ_{ij} denote the period of seasonality and effect of season i, respectively. Since the sum of the seasonal components for all successive times is zero for $t_{j-1}^{\#} < t \leq t_j^{\#}$, S_t can be presented as:

$$S_t = \sum_{i=1}^{s-1} \gamma_{ij} \left(d_{t,i} \ - \ d_{t,0} \right)$$

where $d_{t,i} = 1$ when t is in season i and 0for otherwise. In case, t is in season 0, then $d_{t,i} -\ d_{t,0} = -\ 1$. For other seasons, when t is in season $i\ \neq 0$ then $d_{t,i} -\ \ d_{t,0}\ = 1$. Moreover, $d_{t,i}$ is a dummy seasonal variable with 0 and 1 values to account for seasons in a regression model (Verbesselt et al., 2010). BFAST iteratively fits the seasonal-trend decomposition procedure to detect breakpoints through the following four steps; (i) the ordinary least squares residuals-based moving sum (OLS-MOSUM) test detects the breakpoints in the trend component, the number and position of breakpoints are computed from the seasonally adjusted data; (ii) the trend coefficients are then calculated through a robust regression that is based on M-estimation; (iii) in case OLS-MOSUM test detects breakpoints in the seasonal component, their number and position are estimated from trend adjusted data; and (iv) the seasonal coefficients are calculated using a robust regression based on M-estimation (Verbesselt et al., 2010). For a more detailed explanation of the BFAST method, readers are referred to the original paper (Verbesselt et al., 2010).

This study focused on the time series' trend component to explore the abrupt changes. We implemented BFAST package version 1.5.7 (Verbesselt et al., 2014) in the R statistical software version 3.6.1 (R Core Team, 2020). The irregular time series were extracted, converted to daily and then to monthly time series. We used a seasonal dummy model on a median monthly time series of Landsat data (Verbesselt et al., 2010). This method derives the seasonal component to detect changes in the trend component (Watts & Laffan, 2014). An important parameter to select in implementing BFAST is the h parameter, which determines the minimum segment size, leading to the number of potential trend segments and the number of breakpoints in the trend component (Watts & Laffan, 2014). The higher values of h lead to the omission of several breakpoints, and low values may lead to the detection of false breakpoints. Therefore, we tested different h parameter values on various locations with a known history of flood events to determine the optimal h value. Finally, we assumed $h = \frac{1}{9}$ (i.e., 44 months as minimum segment size) as the appropriate value for this parameter used in this study. The time series results were the number of breakpoints for each pixel, the timing and the magnitude of these breakpoints.

7.3.5 Post-processing and validation of floods

Since we focus on floods that disrupt the vegetation in the valleys resulting in negative abrupt change, we extracted breaks with negative change from BFAST results (Figure 7.2). A mosaic was generated from the tiles, and seasonal analysis was carried out at the catchment level. The detected abrupt change was further analyzed to extract specific disaster events. We demonstrated this approach successfully by exploring known flood events in the village of Ayun (35°43'29.38" N, 71°46' 33.82" E) and three adjacent valleys of Ayun, Rumbur and Kalash (35°39'36"-35°49'1.2" N, and 71°37'58.8"-71°49'55.2" E) in Lower Chitral. The timing and magnitude of the flood events in these sites were verified using spatiotemporal information collected during the fieldwork. The results

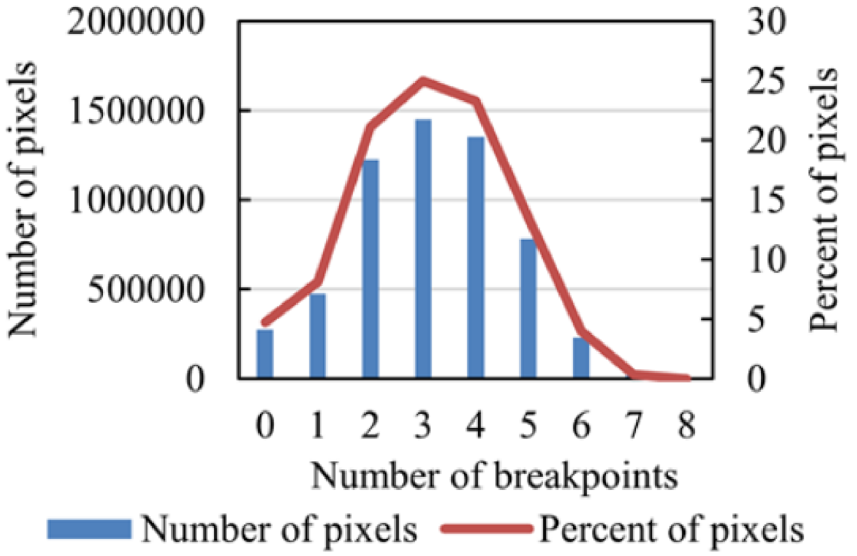


Figure 7.4: Number and percentage of breakpoints per pixel from 1988 to 2020.

were also confirmed through visual interpretation using high-resolution Google Earth imagery before and after the event and documented by photographs taken during the fieldwork.

7.4 Results

7.4.1 Number of breakpoints

The number of breakpoints detected in the time series' trend component varied between zero and eight for each pixel, with most pixels exhibiting between two and four breakpoints (Figure 7.4). Approximately 4.7% (273,139) of the pixels in the valleys did not experience any change, while 95.3(5,524,637) showed at least one abrupt change from 1991 to 2017. The spatial distribution of the breakpoints detected in the time series' trend component is shown in Fig ure 7.5. The statistical results show that 95% of the pixels in the Chitral (3,316,657), Wakhan (107,127) and Swat (498,098) catchments experienced at least one breakpoint. About 91% of the pixels in the Panjkora (410,378) catchment experienced abrupt change, which is the lowest among all the catchments. On the contrary,

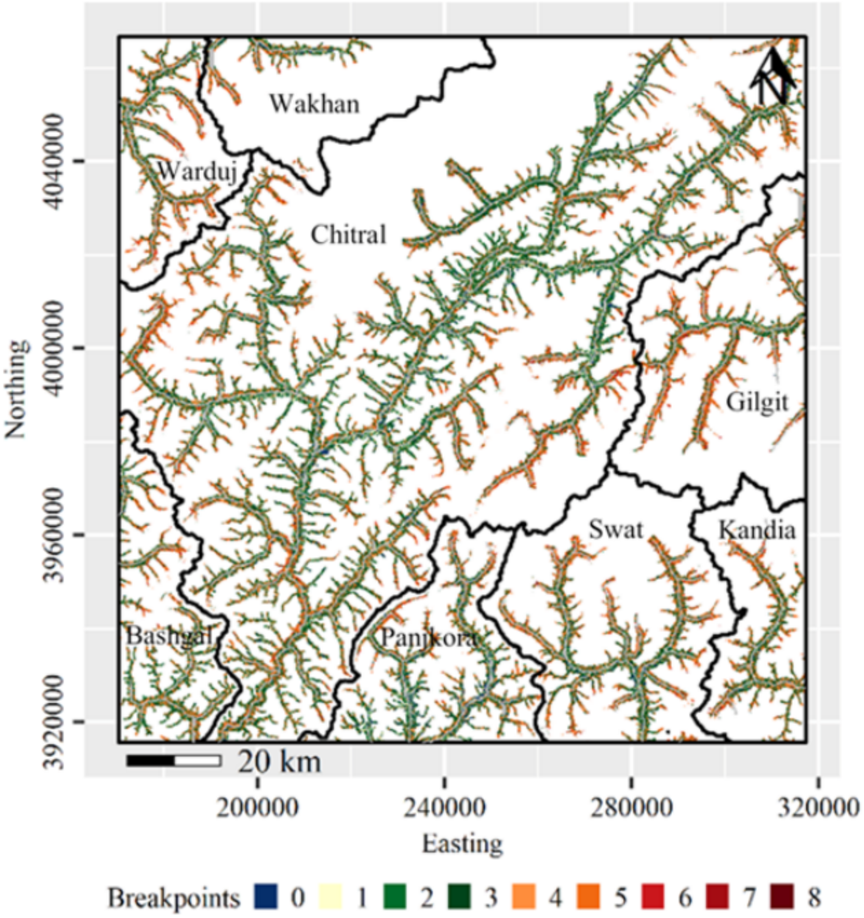


Figure 7.5: Spatial distribution of the number of breakpoints shown in catchments.

the Bashgal catchment had 98pixels (323,555) with breakpoints, the highest among all catchments. About 96% of the pixels in Warduj (279,702) and 97% of the pixels in Kandia (222,447) and Gilgit (366,673) catchments experienced breakpoints.

7.4.2 Annual abrupt changes

Annual negative abrupt change in MSAVI for breakpoints is shown in Figure 7.6. Peak years that experienced significant abrupt change are 1991, 1995, 1998, 2007, and 2016. In 1991 alone, approximately 1,160,613 pixels (20%) exhibited abrupt change making it the year with the highest number of breakpoints. The second significant year was 1998 (1,096,131;

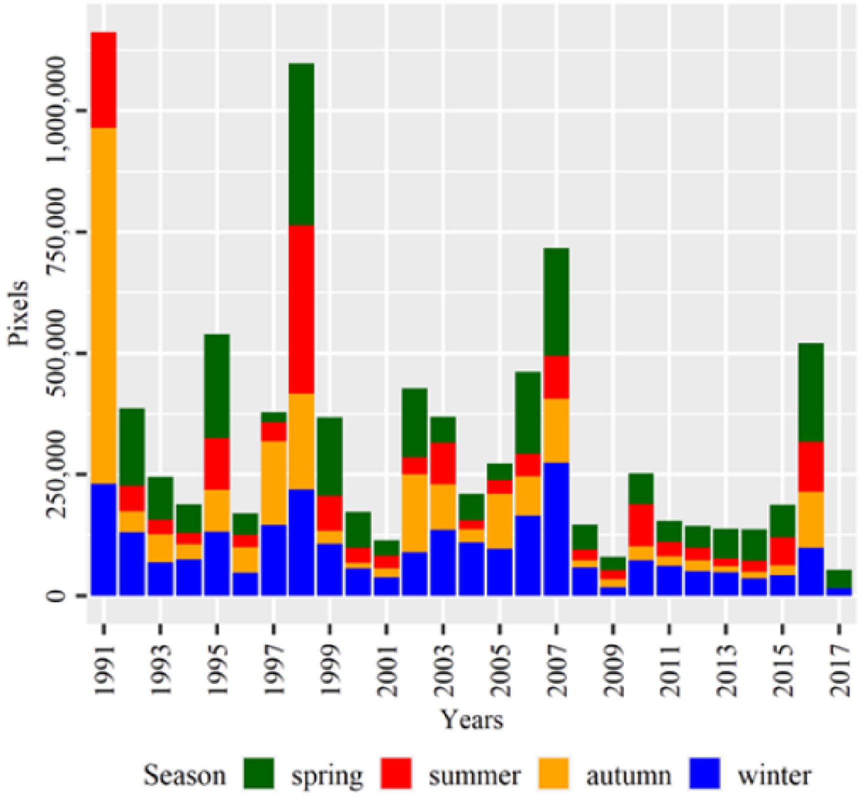


Figure 7.6: Frequency of breakpoints per annum and season from 1991 to 2017.

19% of the pixels) followed by 2007 (716,168; 12% of the pixels) as the third year with the most noticeable change. Eleven years had pixels with an abrupt change between 0.3 and 0.6 million each. The abrupt change is concentrated in different seasons for different years (Figure 7.6). For example, abrupt change in 1991 was strongly concentrated in the autumn while, e.g., in 1998, spring and summer showed the highest number of breakpoints. Overall, the annual trend of abrupt change is on the decline, but each season has different peak years (Appendix 1). For instance, the trend in the autumn season is in fact on the decline; 1991 is the year with the highest peak in this season. The winter season recorded peaks in 1991, 1998 and 2007, also with an overall downward trend. The spring season showed the top three peaks in 1995, 1998 and 2007 respectively with a downward trend, whereas for summer, 1991, 1995 and 1998 remained peak years with an overall decreasing trend.

The spatial distribution of peak years varies in the different catchments, as shown for the examples of 1991 and 2007. In 1991 (Figure 7.7), the abrupt change scattered across eight river catchments in the study area. Approximately 25% of the pixels were affected in Swat (121,205 pixels), Kandia (59,399 pixels), Gilgit (93,330 pixels), Panjkora (112,575 pixels), and Bashgal (82,848 pixels) river catchments. The Chitral river catchment area showed about 19% of the pixels (653,539 pixels) that changed in 1991. Warduj (28,620 pixels) and Wakhan (9,097 pixels) river catchments in eastern Afghanistan were the least disturbed catchments (equal or less than 10% of the pixels). The magnitude of the change for breakpoints was between 0 and -0.5, suggesting a loss of vegetation cover. The negative magnitude of the breakpoint shows the strength of the loss of vegetation. The timing and magnitude of abrupt change in 2007 are shown in Figure 7.8. Most river catchments experienced abrupt change during the winter and spring seasons. Kandia (47,955 pixels) and Swat (113,391 pixels) catchments were the most disturbed (20% of the pixels), while Wakhan (8,833 pixels) and Warduj (24,484 pixels) were least changed (less than 10% of the pixels). Approximately 9% of the pixels changed in the Chitral (316,501) catchment, while 18of the pixels exhibited abrupt change in the Panjkora (79,732) and Bashgal (58,746) catchments in 2007. The magnitude of abrupt change varied between 0 and -0.5, with a large portion of pixels falling in the range of 0 and -0.1.

7.4.3 Analysis of abrupt change at catchment level

Seasonal analysis of abrupt change suggested the peak months varied across different catchments during 1991-2017 (Figure 7.9). November and December were the peak months in Bashgal, Panjkora, Kandia, Chitral, and Gilgit catchments during the 1991-2000 period. June was the peak month in Swat, Wakhan, and Warduj catchments in this decade. Warduj, Gilgit, and Wakhan catchments recorded peak in December during 2001-2010. Bashgal and Chitral's maximum breakpoints were in April, while Panjkora, Kandia, and Swat catchments experienced peaks in February. During the 2011-2017 period, Warduj and Wakhan river catchments ex-

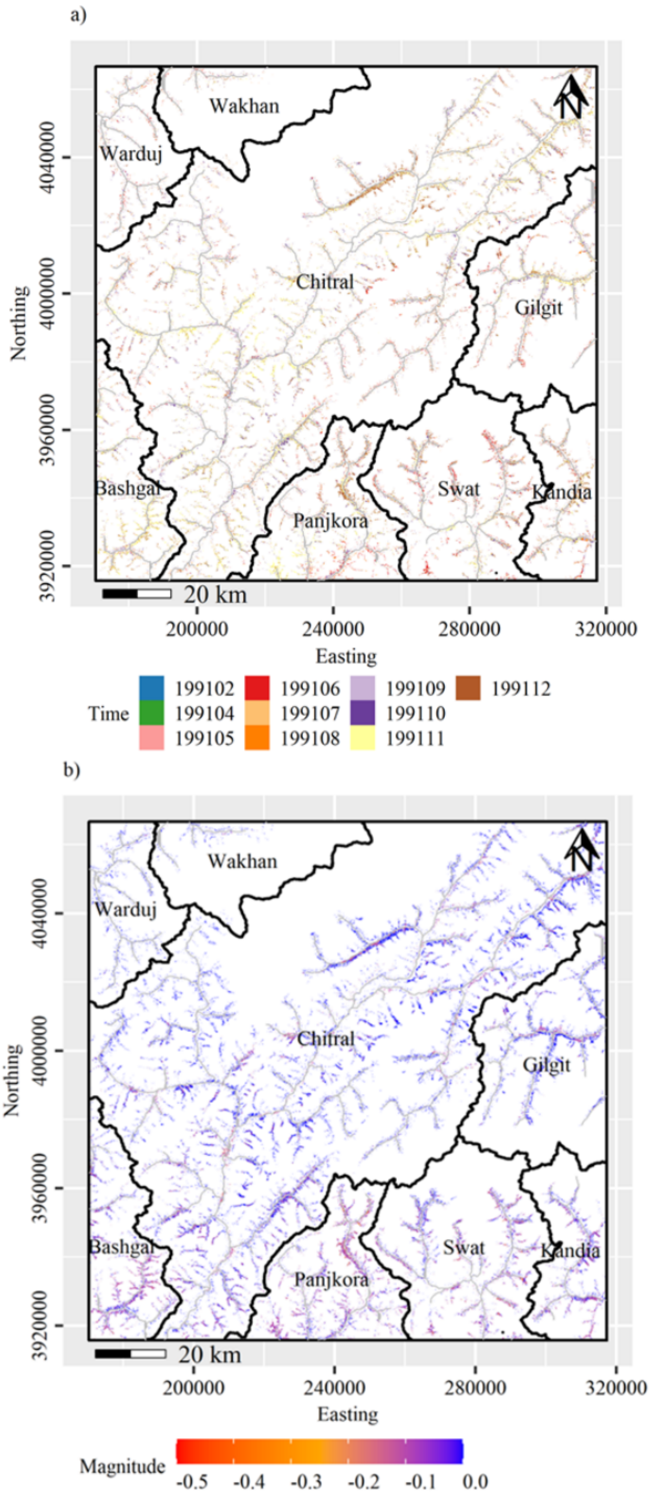


Figure 7.7: The timing of abrupt change in 1991 is spread across Jun – December (a), and the magnitude of abrupt change varied between 0 and -0.5 (b).

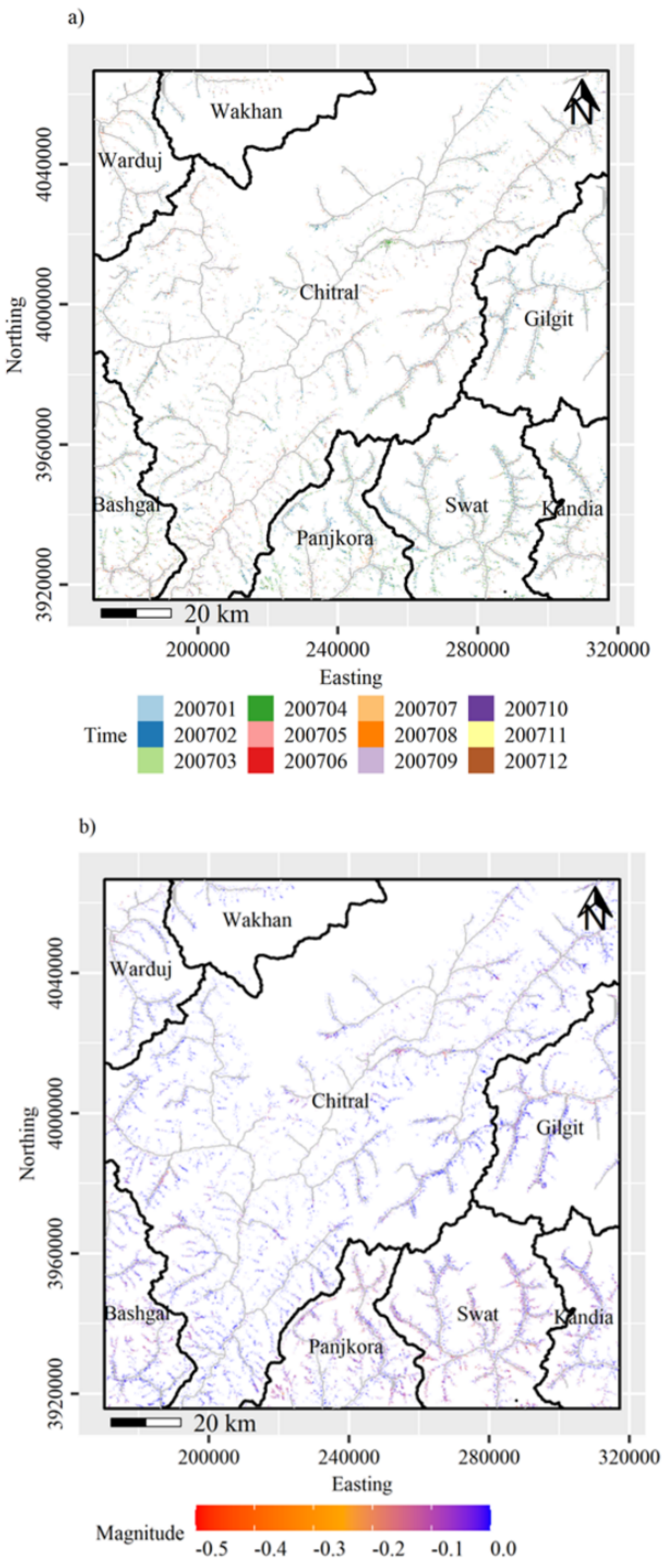
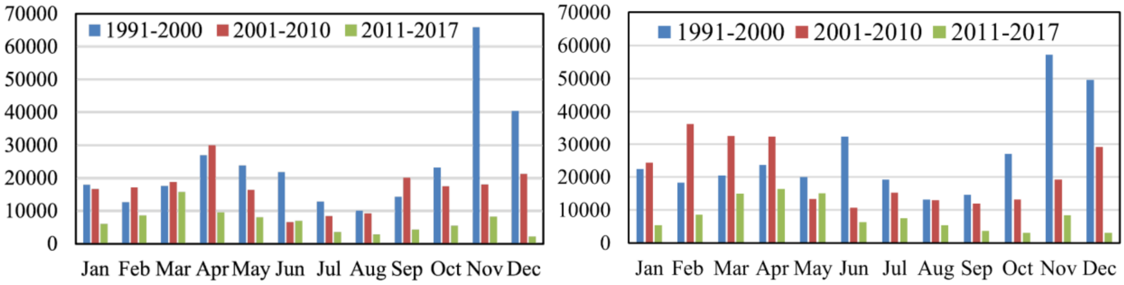


Figure 7.8: The timing of abrupt change in 2007 is spread across the year (a), and the magnitude of abrupt change varied between 0 and -0.5 (b).

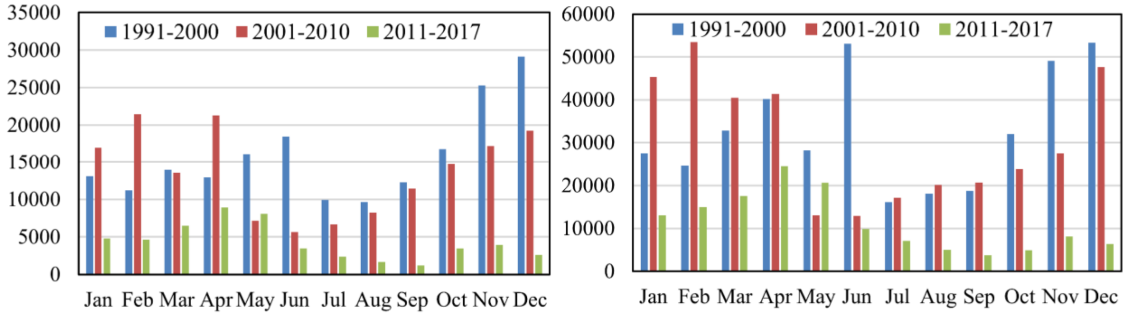
perienced extremes in February, while the highest breakpoints in Bashgal were in March. In the south and southeast of the study area, three adjacent catchments, Kandia, Swat, and Panjkora, showed their peaks in April. The Gilgit and Chitral river catchments' peaks were in May during the last decade. Overall, the number of breakpoints has declined significantly over the decades, especially from October to December. Analyzed at the catchment level, the trends of abrupt change for summer, autumn and winter are decreasing for all the catchments (Appendixes 2-9). The trends in the spring season are decreasing for Warduj, Wakhan, Chitral and Gilgit catchments. On the contrary, Kandia and Bashgal have no trend while Panjkora and Swat catchments showed increasing trends in the spring season.

7.4.4 Detection of flood events

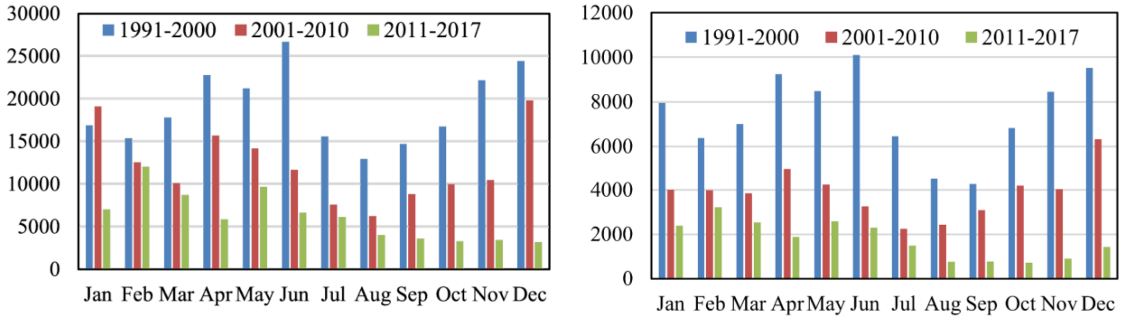
In the Chitral river catchment, a pronounced flood event that was detected in the three adjacent Ayun, Rumbur and Kalash valleys (35°39'36"-35°49'1.2" N, and 71°37'58.8"-71°49'55.2" E) was used for verification. The timing and magnitude of the flood impact extracted from our results are shown in Figure 7.10. The event's timing suggests that the flood occurred in July 2015 and triggered breakpoints in all three valleys. The magnitude of abrupt change was between 0 and -0.4. This flood event damaged housing, crops, bridges, and infrastructure along the streams in the valleys. This result could be confirmed by the interviews and the visual inspection of Google Earth imagery. Figure 7.11(a), dated 27/08/2010, shows the state of vegetation, river and other infrastructure before the flood event in a trench of Kalash valley. Figure 7.11(b), dated 24/09/2019, which is after the July 2015 floods, clearly shows the widening of the riverbanks and damage to vegetation and infrastructure by flood along the riverbanks. The devastation caused by this flooding in Batrik village of the Kalash valley was documented by field photographs (Figure 7.12). Furthermore, we investigated the impact of floods in the village of Ayun (35° 43' 29.38" N, 71° 46' 33.82" E). It was affected by floods in the Chitral river in February and July 2015, resulting in the loss



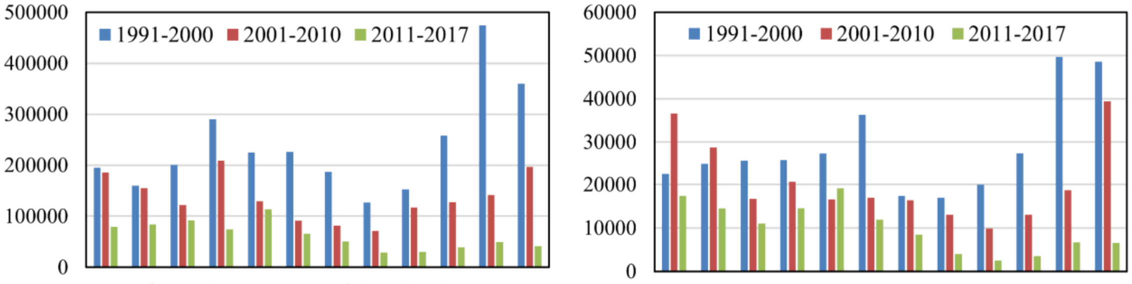
(a) Bashgal (b) Panjkora



(c) Kandia (d) Swat



(e) Warduj (f) Wakhan



(g) Chitral (h) Gilgit

Figure 7.9: Monthly distribution of decadal abrupt change at catchment level: (a) Bashgal; (b) Panjkora; (c) Kandia; (d) Swat; (e) Warduj; (f) Wakhan; (g) Chitral and (h) Gilgit catchments.

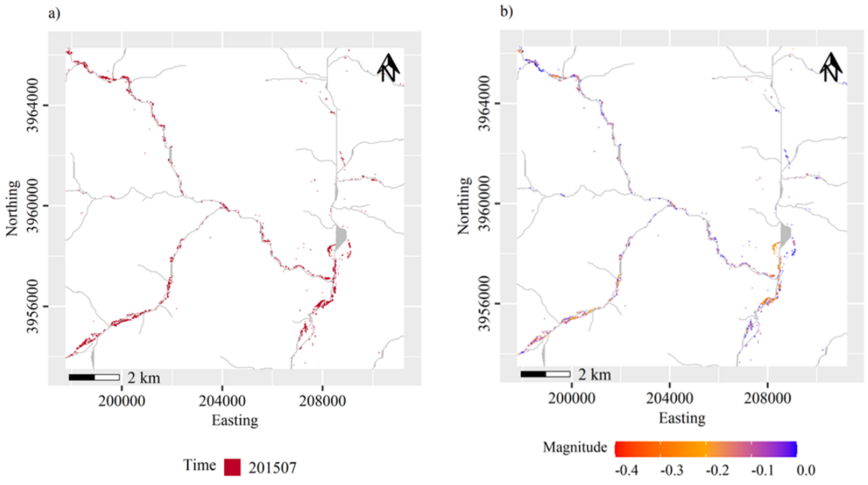


Figure 7.10: 2015 flood detected in Ayun, Rumbur, and Kalash valleys of lower Chitral (a), and magnitude of the flood in July 2015 amounted between -0.4 – 0 (b).

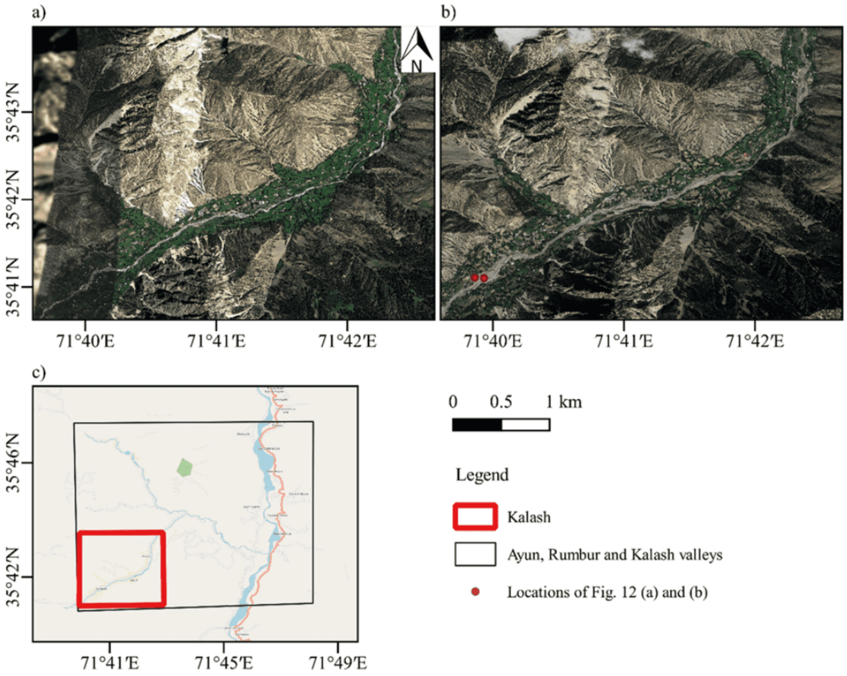


Figure 7.11: The pre and post-historical imagery of the July 2015 flood in Kalash valley taken from Google Earth: (a) image before the flood on 27/08/2010; (b) the damage and deposition of debris in the flood plain caused by the July 2015 flood can be seen in the image of 24/09/2019 and (c) the location of the trench in the Kalash valley. Locations of Fig. 12 (a) and (b) are shown in Fig. 11 (b). (Image source: Google Earth; Map source: Open Street Map)

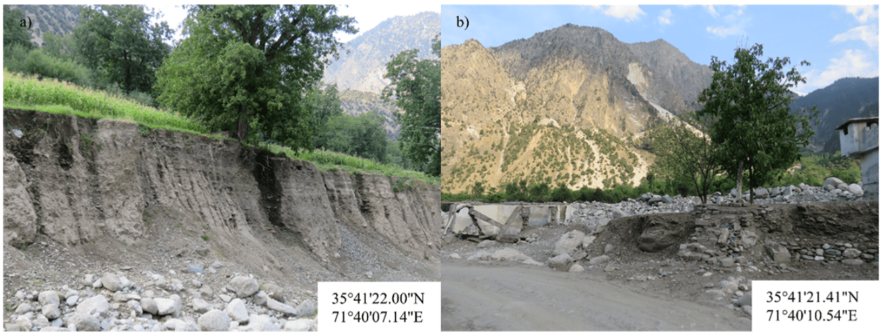


Figure 7.12: Photographs taken during a field visit showing the impact of the July 2015 flood. a) View of the eroded cropland along the riverbanks in Batrik; (b) View of damaged roads, trees, houses, and deposited debris in Batrik village of Kalash valley (August 9, 2020, S.A. Khan).

of cropland and trees. The area affected by each flooding spell is shown in Figure 7.13(a), while the corresponding change in magnitude is shown in Figure 7.13(b). In our results the timing and magnitude of the event were accurately detected. The negative change of MSAVI is attributed to the impact of the flood events due to the loss of vegetation cover caused by erosion. This result could also be confirmed using high-resolution historical imagery from Google Earth (Figure 7.14) and field photographs (Figure 7.15).

7.5 Discussion

Breakpoints, affecting 95.3% of all pixels, are spatially distributed across all the catchments in the study area (Figure 7.5). The high number of pixels with breakpoints suggests that vegetation cover has experienced extensive change. This change can be attributed to both anthropogenic and environmental factors. Besides the recurring flood events affecting the vegetation in the valleys along the eastern Hindu Kush rivers (Nibanupudi & Shaw, 2015; Tsering et al., 2021), boulder fall is a widespread hazard as indicated by field observations but is unlikely to affect an entire pixel or several pixels. Similarly, landslides and avalanches are also recurring hazards in our study area. Still, they have a different spatial pattern

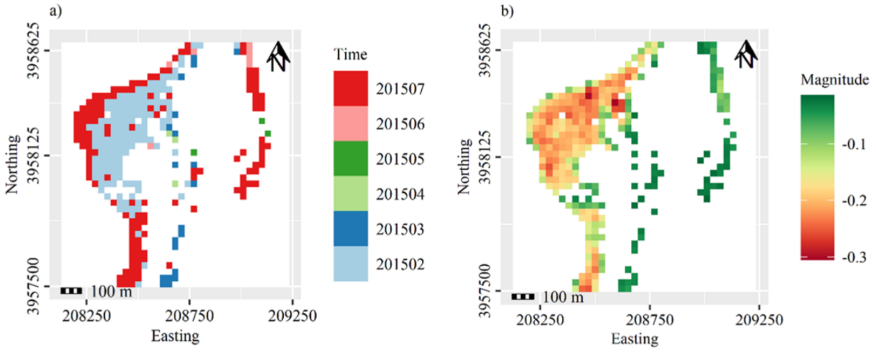


Figure 7.13: BFAST results produced for Ayun using MSAVI, NDVI, and NDWI. The vegetation loss due to floods was detected in February and July 2015 (a), with a reduced magnitude for MSAVI and NDVI and increased magnitude for NDWI (b). The location of the Ayun site is shown in Fig. 14.

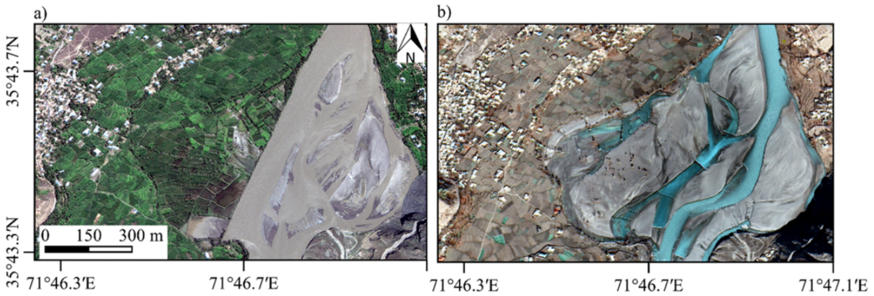


Figure 7.14: Imagery from Google Earth: a) pre-flood image of Ayun on 08/27/2010 and b) post-flood image on 11/30/2018. (Source: Google Earth)

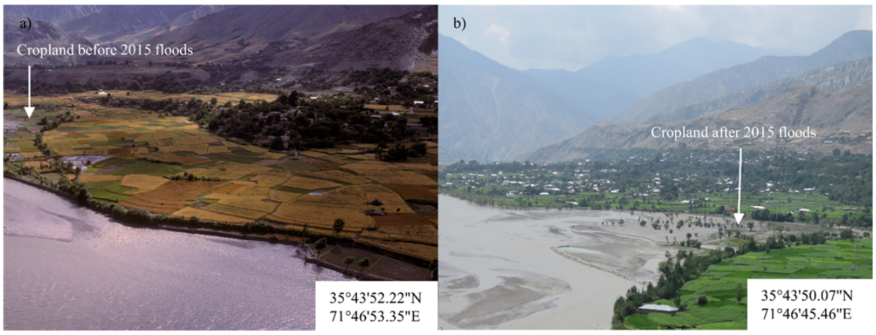


Figure 7.15: View of Ayun before and after the 2015 flood. a) shows the thriving cropland along the riverbank (June 12, 1997, M. Nüsser); b) shows the eroded cropland by 2015 floods in the Chitral River (August 9, 2020, S.A. Khan)

than the abrupt changes by floods that occur simultaneously in connected areas along the valley floors. Anthropogenically induced changes include construction works, clear-cuts, and abandonment or redevelopment of land, which are expected to cause patchy and incoherent patterns.

We noticed that the upper catchments experienced more breakpoints than the lower catchments (Figure 7.5). The high number of breakpoints is possibly due to the occurrence of flash floods in the upper catchments, which are usually caused by intense rainfall in addition to heavy snow and glacial melting (Ashraf et al., 2021; Nibanupudi & Shaw, 2015). The pixels experiencing vegetation loss are aligned along the river courses, which suggests flooding as the cause. Smaller catchments in the upper valleys react more to locally heavy precipitation than to large-scale inundation, which is why we assume flash floods to be the cause there. This interpretation is supported by our field observations showing high sediment transport typical of hyper-concentrated flows and debris flows. Flash floods could cause more damage than riverine floods due to their high velocity, little or no early warning, and relatively higher concentration of debris than riverine floods. In the smaller valleys, fewer settlements are affected by flash floods because they are sparsely populated.

On the other hand, the lower catchments are susceptible to the riverine floods caused by water overflows in the rivers and their impact on crops, lands, infrastructure, and human lives in the floodplains. The breakpoints with a negative magnitude of change are concentrated in the valleys along the rivers rather than on the mountains' slopes which shows that flooding is, quantitatively, the most critical hazard in this area. This confirmed our presumption that the negative changes co-occur in connected areas along the rivers, while positive changes are more scattered with single pixels.

Negative abrupt change is scattered across the entire time series. 1991, 1995, 1998, 2007, and 2016 appeared as the peak years during the 1991-2017 period (Figure 7.6). Breakpoints in these peak years are distributed across different seasons. The abrupt change is concentrated in autumn for 1991, in winter for 2007, and in spring for 1998 and 2016. The spatial distribution of abrupt change shows that the breakpoints were concentrated in southern catchments of Swat, Kandia, Panjkora, Gilgit and Bashgal in 1991. Kandia and Swat, the southern catchments, again were affected by the abrupt change in 2007. The region is characterized by complex climatology where various local and regional climatic conditions influence events in different seasons. The exact determination of the drivers of these seasonal peaks requires a sophisticated climatological approach beyond the scope of this study. In general, summer events are caused by summer monsoon rainfall extremes which are influenced by the Madden Julian Oscillation, Indian Ocean Dipole, and indirectly by El Niño Southern Oscillation (Gadgil et al., 2004). Winter and spring events are influenced by the Northern Atlantic Oscillation and the Siberian High (Syed et al., 2006). Spring events are possibly caused by heavy snowfall in winter and the early melting of glaciers and snow in spring (Ahmad et al., 2018; Shahid & Rahman, 2021). Moreover, intense summer events are related to a strong summer monsoon (Webster et al., 2011). Interestingly, e.g., 2010 with a strong monsoon has comparably low abrupt changes in the summer season.

The trends for summer, autumn, and winter are decreasing for all the catchments, while mixed trends can be noticed in the spring season (Appendixes 2-9), with two catchments (i.e., Panjkora and Swat) showing increasing trends, and Bashgal and Kandia exhibiting no trend. This upward trend could be due to the different climatic conditions (relatively high rainfall, vegetation patterns etc.) in the southern part compared to other regions in our study area. Chitral catchment has diverse climatic conditions, with southern valleys receiving more rainfall than the valleys in the north. It may also have different seasonal trends for the southern and northern parts. Overall, the decreasing annual trend can be attributed to the decreasing annual rainfall trend in the Upper Indus Basin as argued by other hydrometeorological studies (Latif et al., 2018; Yaseen et al., 2020). The increasing trend in the spring season in some of the catchments is probably influenced by the increase in glacial and faster snow melt caused by a rise in temperature in spring (Baig et al., 2021; Shahid & Rahman, 2021).

Through the spatiotemporal exploration of the BFAST results, we were able to trace the timing and spread of specific flood events, e.g., the flooding of 2015 in Ayun, Rumbur, and Kalash valleys (Figure 7.5, 7.13). The results were interpreted using a mixed approach comprising visual interpretation and historical imagery and fieldwork. Overall, both the historical floods were reflected by major breakpoints, but there are many other isolated breakpoints for which no corresponding record was found. Natural hazards such as rockfalls and landslides are challenging to detect due to the lack of accurate information on their occurrence and smaller size. As stated earlier, these isolated events could also be triggered by anthropogenic activities such as deforestation and undercutting of the slopes for building roads and other infrastructure. Flooding can only be discerned from anthropogenic activities through its coherent patterns and proximity to the river network. This limitation can be overcome by using land cover classification to understand changes in land cover types. However, the BFAST method cannot be used on its own to explore the change in land cover classes. For future studies, we think of applying new techniques such as Prophet and dynamic time warping based time series classification approach and deep learning based time series classification that already showed promising results (Rußwurm & Körner, 2020; J. Yan et al., 2019).

This study is the first attempt to explore abrupt change in the land cover using BFAST and Landsat image time series in the complex terrain (i.e., arid, semi-arid environment, high mountain region, diverse vegetation cover influenced by strong seasonality of precipitation) of the eastern Hindu Kush. Our findings indicate that the region and its catchments experienced significant, abrupt changes in land cover from 1988 to 2020. The methodological approach enables us to understand the spatiotemporal patterns and to extract past flood events. Moreover, our research method can furnish a flood disaster database for this area. In addition, it provides a historical spatiotemporal analysis of the past floods and their impact in various valleys. Finally, the results and methodology are meant to support policymakers and disaster management practitioners to prepare future hazard risk assessments and disaster management plans for the eastern Hindu Kush mountain communities.

7.6 Conclusion

In this study, the spatial and temporal patterns of abrupt change in land cover in the eastern Hindu Kush valleys were investigated using BFAST based on Landsat-derived MSAVI times series from 1988 to 2020. The study confirmed the applicability of the BFAST method to detect abrupt change in the complex environment of this high mountain region. Our study showed that all three research questions were answered, which is reflected in the conclusions:

1. The study results indicate that only 5% of pixels remained stable, while 95% experienced a minimum of one breakpoint from 1988 to 2020. The occurrence of a high proportion of breakpoints suggests that vegetation has undergone extensive change in the eastern Hindu Kush region. Moreover, many breakpoints were detected in the upper catchments of streams and rivers, indicating their high susceptibility to flash floods.

2. 1991, 1995, 1998, 2007, and 2016 appeared as the peak years for abrupt change. There were a few years with heavy rainfall events which are not detected, e.g., the strong monsoon rains in 2010. At the same time, the peak years vary for each season. Peak years in different seasons are probably caused by a complex interplay of several climatic circulation patterns, which influence precipitation patterns in the region. Summer, autumn, and winter seasons showed downward trends for all catchments, while Kandia and Bashgal have no trend, and Swat and Panjkora catchments showed upward trends in the spring season.

3. The concentration of negative abrupt change in the floodplain suggests that floods are major natural processes that trigger debris

flows and river erosion in our study area. These natural hazards cause damage and loss of agricultural land, housing, and other community infrastructure. Their impacts were shown by examples of the 2013 and 2015 floods in Kalash, Rumbur, and Ayun valleys of Chitral.

4. BFAST applied to Landsat-derived MSAVI time series data can be very useful to analyze past natural processes in high mountain regions such as the eastern Hindu Kush. The approach involving analysis of abrupt change at different levels, number of breakpoints at catchment level, annual and seasonal change, and the extraction of events in specific valleys enabled us to understand the land cover change in the region.

5. Future research should investigate the abrupt change in land cover by integrating BFAST results with social research (e.g., survey questionnaires and interviews) to explore the impacts of natural hazards on mountain communities.

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Chapter 7

Appendix

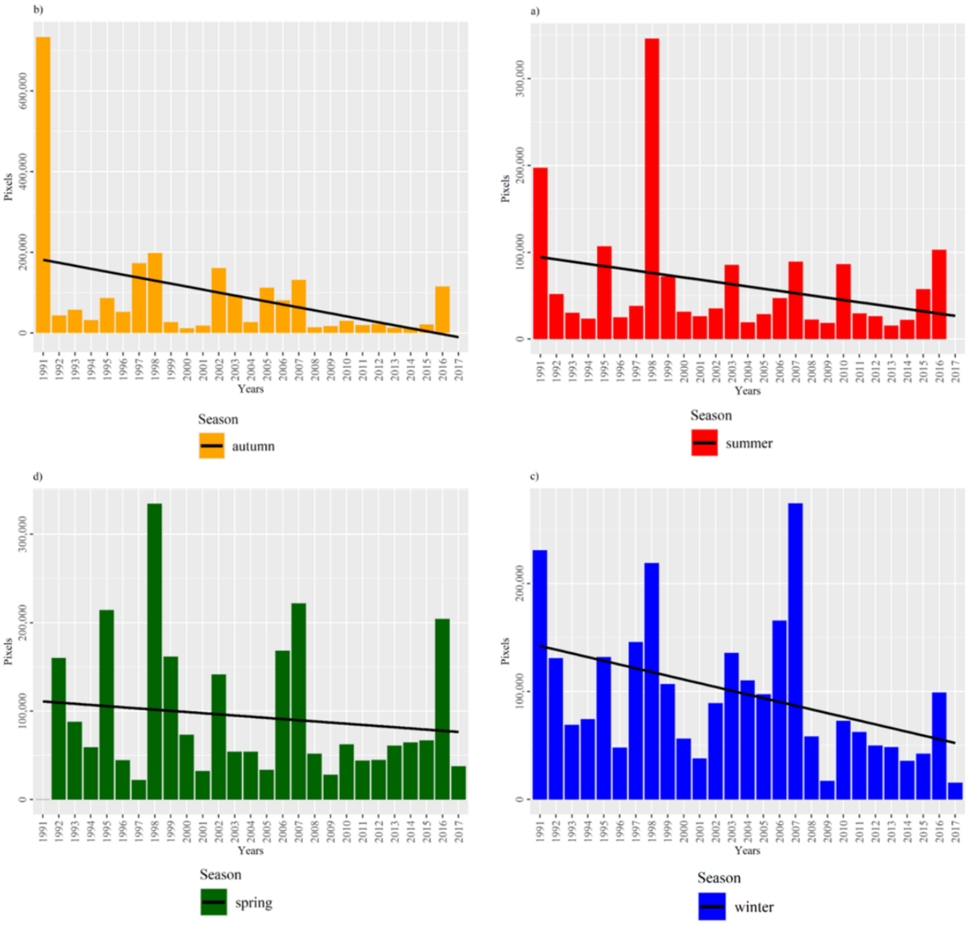

Figure 7.16: Appendix 1. Distribution of annual abrupt change in the study area for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

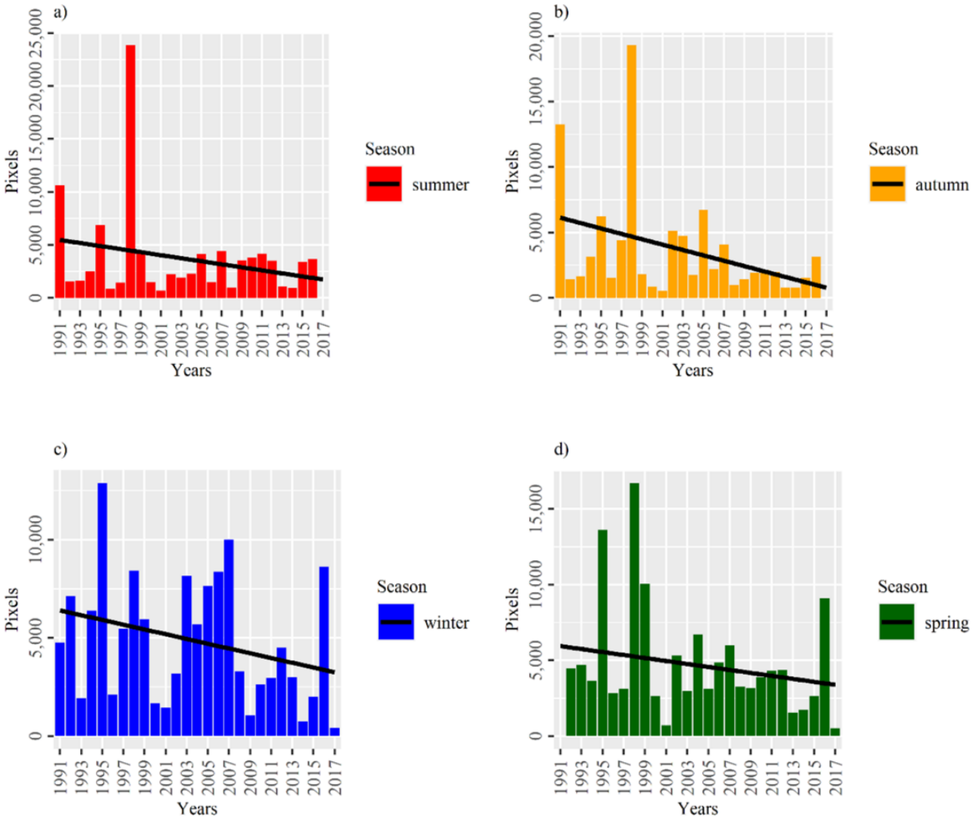

Figure 7.17: Appendix 2. Distribution of annual abrupt change in Warduj catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

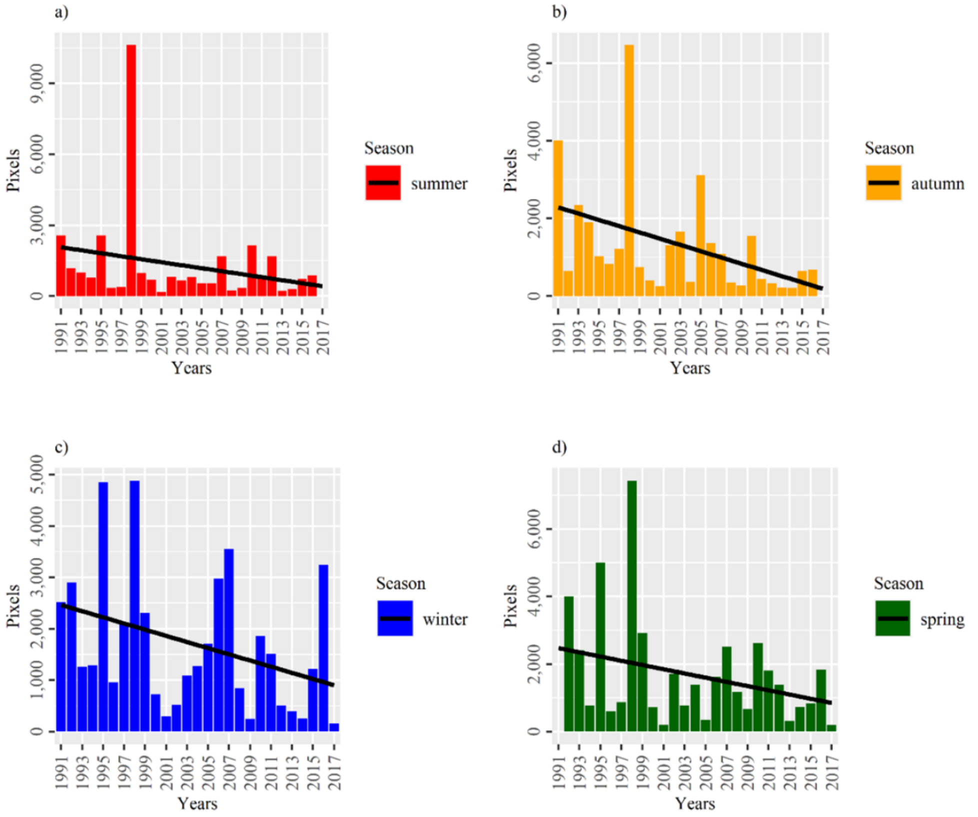

Figure 7.18: Appendix 3. Distribution of annual abrupt change in Wakhan catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

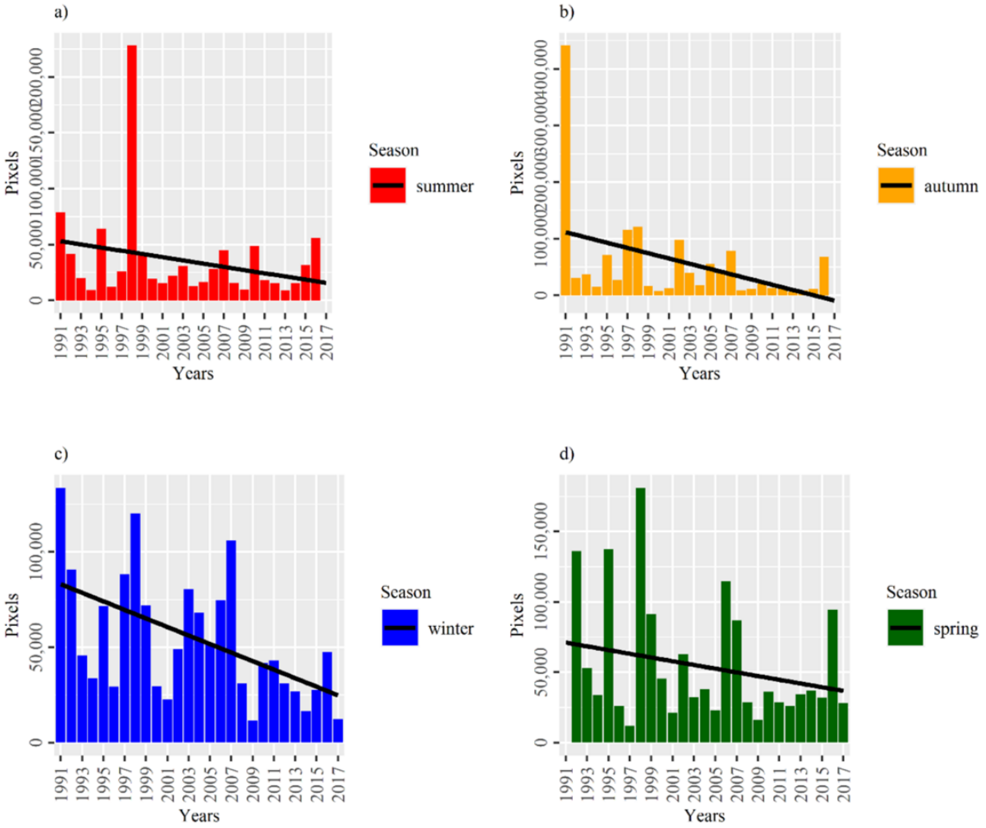

Figure 7.19: Appendix 4. Distribution of annual abrupt change in Chitral catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

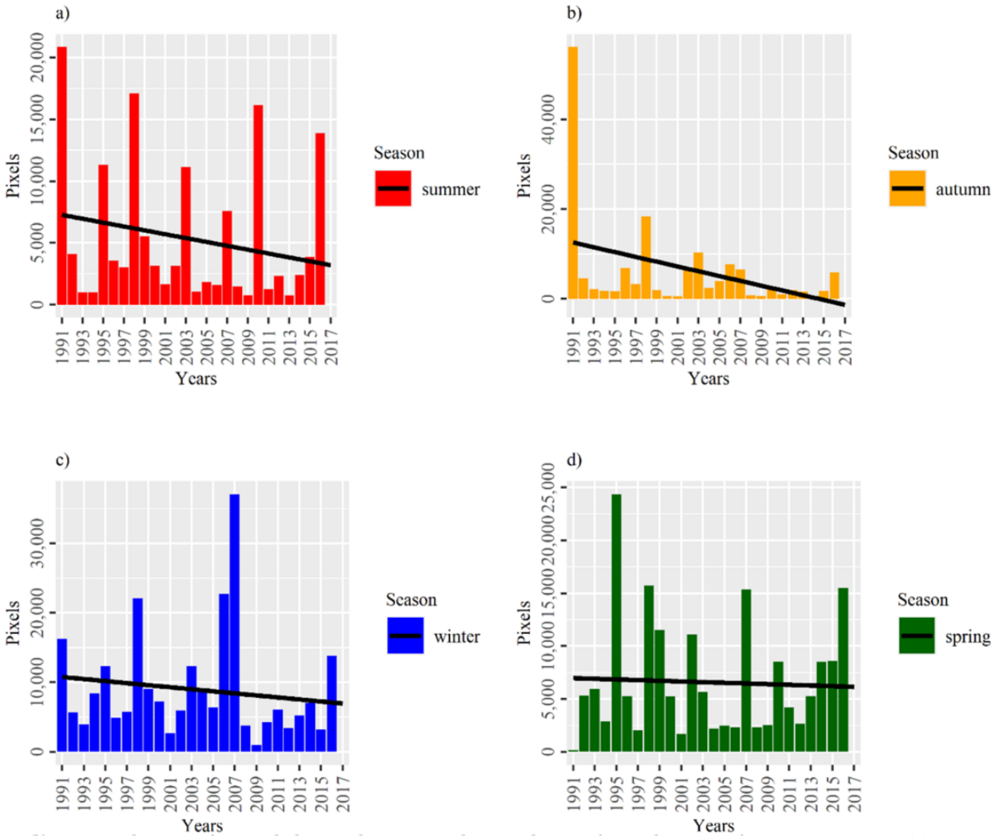

Figure 7.20: Appendix 5. Distribution of annual abrupt change in Gilgit catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

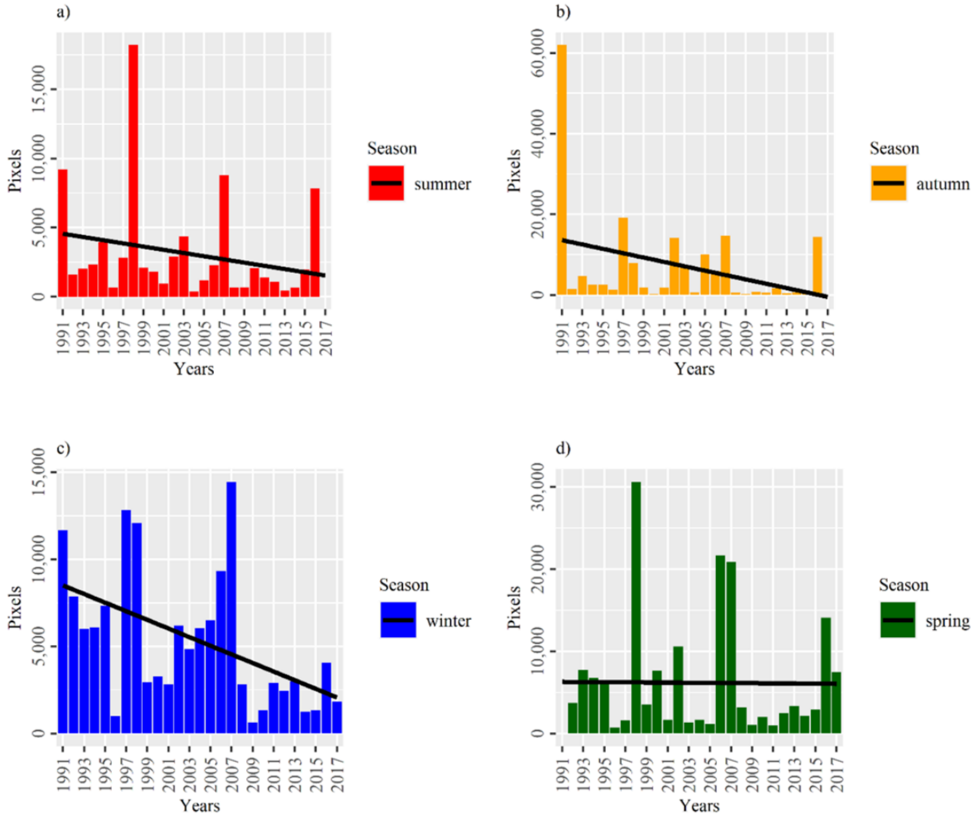

Figure 7.21: Appendix 6. Distribution of annual abrupt change in Bashgal catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

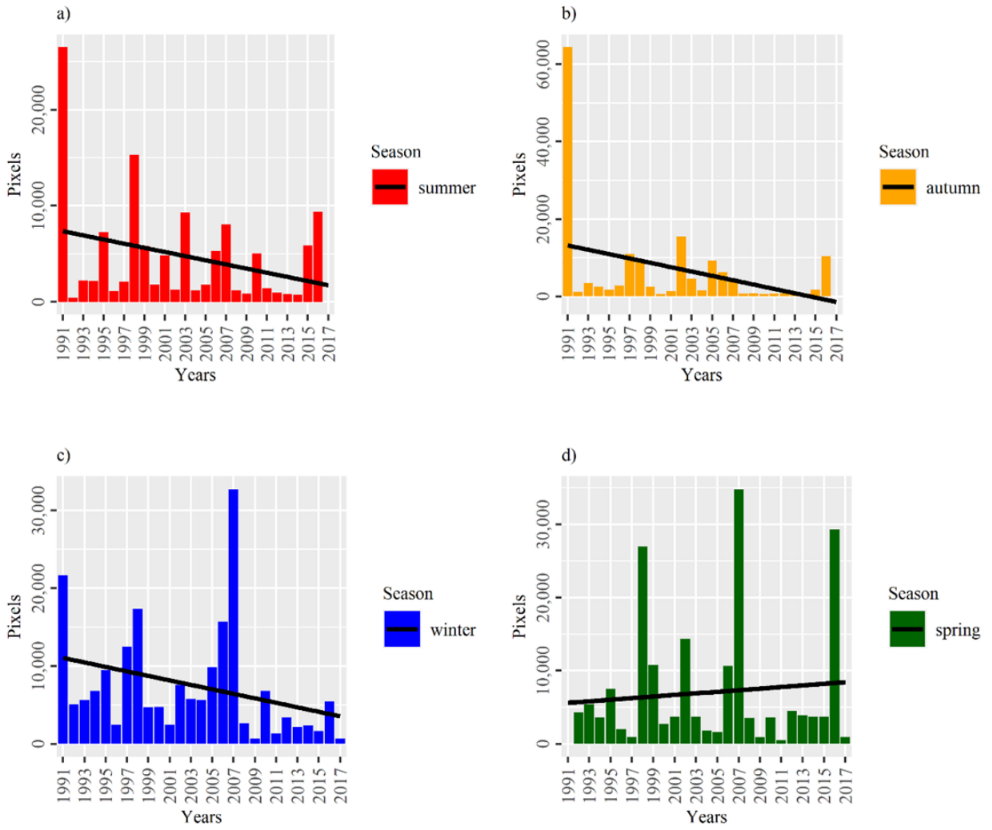

Figure 7.22: Appendix 7. Distribution of annual abrupt change in Panjkora catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

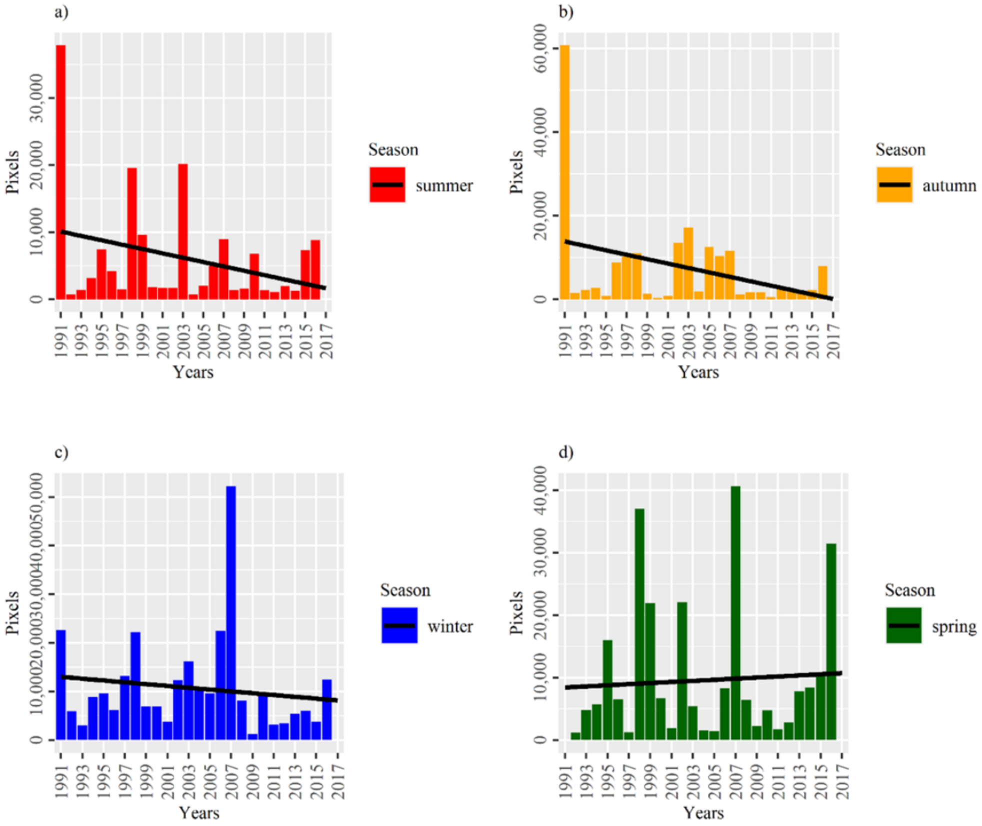

Figure 7.23: Appendix 8. Distribution of annual abrupt change in Swat catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

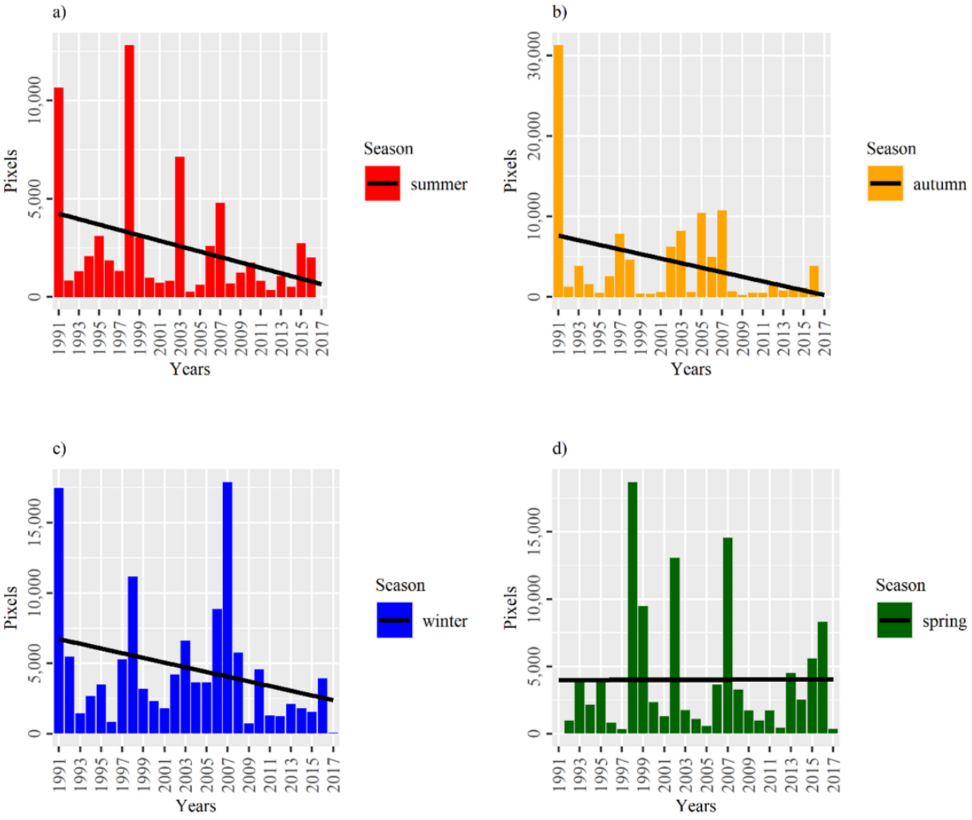

Figure 7.24: Appendix 9. Distribution of annual abrupt change in Kandia catchment for each season from 1991 to 2017: (a) summer; (b) autumn; (c) winter and (d) spring season. The trend line indicates the direction of the trend.

8. Manuscript III: Vegetation Trend Detection Using Time Series Satellite Data as Ecosystem Condition Indicators for Analysis in the Northwestern Highlands of Ethiopia

Outline

Bibliographic Information

Alemayehu, B., Suarez-Minguez, J., Rosette, J., & Khan, S. A. (2023). Vegetation Trend Detection Using Time Series Satellite Data as Ecosystem Condition Indicators for Analysis in the Northwestern Highlands of Ethiopia. Remote Sensing, 15(20), 5032. `https://doi.org/10.3390/rs15205032`

Article Adaptation

The contents of the original version had to be slightly modified for its inclusion in this dissertation, including the numeration of sections, figures, tables, and equations had to be adjusted. The published version of this article can be found at `https://doi.org/10.3390/rs15205032`.

Abstract

Vegetation is an essential component of the terrestrial ecosystem and has changed significantly over the last two decades in the Northwestern Highlands of Ethiopia. However, previous studies have focused on the detection of bitemporal change and lacked the incorporation of entire vegetation time series changes, which are considered significant indicators of ecosystem conditions. The Normalized Difference Vegetation Index (NDVI) time series dataset from the Moderate-Resolution Imaging Spectroradiometer (MODIS) is an efficient method for analyzing the dynamics of vegetation change over a lengthy period using remote sensing techniques. This study aimed to utilize time series satellite data to detect vegetation changes from 2000 to 2020 and investigate their links with ecosystem conditions. The time series satellite processing package (TIMESAT) was used to estimate the seasonal parameter values of NDVI and their correlation across the seasons during the study period. Break Detection for Additive Season and Trend (BFAST) was applied to identify the year of breakpoints, the direction of magnitude, and the number of breakpoints. The results were reported, analyzed, and linked to ecosystem conditions. The overall trend in the study area increased from 0.58 (2000–2004) to 0.65 (2015–2020). As a result, ecosystem condition indicators such as peak value (PV), base value (BV), amplitude (Amp), and large integral (LI) exhibited significant positive trends, particularly for Acacia decurrens plantations, Eucalyptus plantations, and grasslands, but phenology indicator parameters such as start of season (SOS), end of season (EOS), and length of season (LOS) did not show significant trends for almost any vegetation type. The most abrupt changes were recorded in 2015 (24.7%), 2012 (18.6%), and 2014 (9.8%). Approximately 30% of the vegetation changes were positive in magnitude. The results of this study imply that there was an improvement in the ecosystem's condition following the establishment of the Acacia decurrens plantation. The findings are considered relevant inputs for policymakers and serve as an initial stage for the assessment of the other environmental and climatic implications of Acacia decurrens plantations at the local scale.

8.1 Introduction

Vegetation is one of the main elements in terrestrial ecosystems [1], and is directly connected to a variety of ecosystem services, such as soil retention, water infiltration, and carbon sequestration [2]. Through the process of photosynthesis, vegetation regulates the exchange of energy and water vapor, influencing their interaction between the Earth's surface and the atmosphere [3], and it plays an essential role in ecological conservation and restoration [1].

Vegetation cover changes over time due to various anthropogenic or environmental drivers, such as increased agricultural activities, residential development, livestock husbandry, and climate change [4]. Changes in vegetation trends reflect environmental changes at different temporal and spatial scales [5].

These changes influence the structure and services, and it is important to monitor them to inform decision makers about the design of strategies for sustainable resource management [6,7]. The acquisition of time series imagery from Earth observation satellites with frequent worldwide coverage makes it possible to monitor vegetation trends by recognizing and interpreting changes within these datasets [5].

Earth observation science has developed a set of tools that are widely applicable for monitoring the temporal and spatial trends in vegetation status [8]. Medium-resolution optical satellite imagery, which is abundant and widely available, is a valuable tool for monitoring ecosystem changes and disturbances over time [7]. For example, Landsat and the Moderate-Resolution Imaging Spectroradiometer (MODIS) are widely used in ecosystem studies owing to their free availability [9]. Landsat data have been utilized to acquire ecological information, such as ecosystem services modeling and land cover change detection, over the last few decades [10]. However, the 16 day revisit cycle and cloud contamination limit its applicability for monitoring biophysical processes and surface changes [11]. Since the beginning of 2000, MODIS has provided improved temporal resolution and intermediate spatial resolution (250 m) data resources, covering the globe with scientifically reliable spatial data sources [12]. It has undergone rigorous validation with enhanced satellite products [13] and assists in the extraction of essential information for time series ecosystem condition research [12].

Sensor capabilities in terms of temporal, spatial, and spectral resolutions have considerably improved in recent years and deliver more information with better precision [14]. Consequently, more complex analysis employing novel algorithms to detect changes in vegetation cover using time series data is becoming more prominent [15].

Vegetation indices (VIs) are the most commonly applied data transformation techniques for assessing and monitoring vegetation changes [16], wherein the vegetation signal is enhanced across certain parts of the spectrum, and the data are more valuable when at least two bands are combined into a VI [17]. Likewise, when VI time series are generated, they provide information on the dynamic patterns of vegetation [18]. At this point, the time series can be used to extract useful metrics, such as trends, seasonal variations [19], and abrupt breakpoints [20]. Decomposing time series data into their components allows us to recognize each element of the series independently.

Seasonal changes, which define the vegetative state and seasonal development, form the basis of phenological studies [21], determining interannual vegetation changes in terrestrial ecosystems [22]. They also serve as indicators of vegetation productivity changes [23] and play a crucial role in assessing climate–vegetation interactions [24]. Interannual changes can be used to track multi year land surface modifications and conversion processes [21]. They are widely accepted as leading indicators of ecological response to climate variation [25]. Changes in the trend component also suggest the existence of human activities (afforestation or deforestation) and disturbances (e.g., fires).

The Normalized Difference Vegetation Index (NDVI) is one of the most prevalent metrics that provides a good indication of vegetation change in seasonal and interannual variations in vegetation and the environment [17] and is the most used VIs in phenological studies [23]. The time series NDVI has been used to extract numerical observations related to vegetation dynamics [26] and to depict the growth status of vegetation, along with its dynamic interactions and changes in land use [27].

In Fagita Lekoma District, the primary threat was land degradation caused by soil erosion, particularly gully erosion due to water runoff. This was evident from the presence of numerous gullies in various areas. To alleviate this problem, adopting land use practices that can provide economic benefits for farmers and contribute to environmental sustainability, such as planting selected commercial trees, could significantly improve the sustainable use of natural resources. From this perspective, plantation forests can generate additional income for farmers [28], reduce poverty [29], provide firewood [30], improve soil fertility and health [31], improve degraded ecosystems [32], and contribute to curbing global warming by sequestering more carbon from the atmosphere [33].

In this district, Acacia decurrens plantations have been developed for the last two decades. As a result, forest cover has expanded at the expense of other types of land use/land cover, such as croplands and grasslands [34–38]. However, previous studies in the district were based on a bitemporal approach that focused on comparing images at two different times. This approach is commonly used in change detection methods because of its advantages of simple mathematics and low storage consumption, but it lacks comprehensive information on the dynamics of the Earth's surface [15]. The time series change detection approach provides more information in a single analysis, such as the type and consistency of the changes [39]. Moreover, considering the entire time series enables the characterization of the temporal vegetation dynamics of clear cuts and restorations by detecting both abrupt and gradual changes [40]. Positive and negative changes in vegetation growth are indicators of the ecosystem status [41]. The underlying process of change can be obtained from the temporal trajectory of a given pixel with different curve shapes, which can be interpreted as an ecological response [42]. Therefore, this study aimed to utilize satellite time series data to detect seasonal and interannual vegetation changes and investigate their linkage with ecosystem conditions.

The vegetation cycles reveal significant short and long term ecological processes [21]. The results of this study are important to demonstrate the role of plantation forests in determining vegetation trends and their implications for ecosystem conditions at the local scale. Furthermore, it can be utilized to demonstrate the contribution of the local community to vegetation regeneration and ecosystem improvement.

8.2 Materials and Method

8.2.1 Study Area

This study was conducted in the Northwestern Highlands of Ethiopia, specifically in Fagita Lekoma District. The total area of the district is 65,579 ha [34], and it is located at 10°56 –11°12 N and 36°40 –37°06 E (Figure 8.1). The landscape is characterized by rugged and undulating topography, with elevations ranging from 1879 to 2922 m above sea level. Climatic conditions include humid subtropical (Weynadega) and moist subtropical (Dega) agroecological zones, which cover 84% and 16% of the study area, respectively [34]. The mean annual precipitation of the area is 2454 mm yr—1, and the peak rainfall occurs between June and September, with a unimodal rainfall pattern. The mean daily temperature ranges from 15 °C to 24 °C [43]. In 2015, the main types of land use/land cover in the district were cultivated land (56%), grasslands (23%), forests (19%), and urban areas (2%) [34]. In the last two decades, plantation forests have become among the dominant land use types due to the expansion of Acacia decurrens plantation forests. Acacia decurrens is a fast growing exotic tree species that is extensively grown in the district by small scale farmers [44]. Acrisols are the dominant soil type in the district and are characterized as severely weathered, acidic soils [45]. Most of the steep slope areas of the district are covered with Leptosols, which are thin, degraded soils. The district is drained by various streams flowing westward and northeastward to join the Tinbil and Abay Rivers, respectively (Figure 8.1).

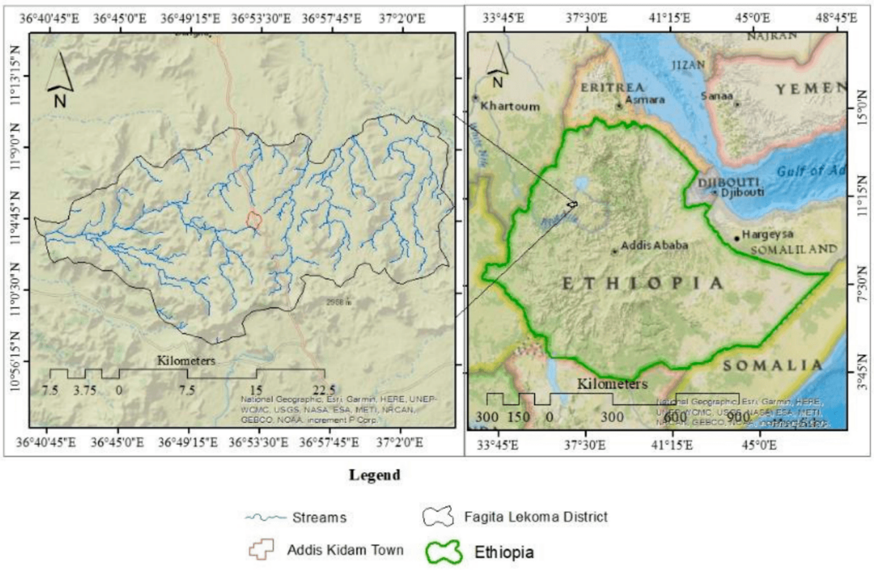

Figure 8.1: Location map of Fagita Lekoma District.

8.2.2 Data

Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra satellite vegetation index products (MOD13Q1, h21v07) with 250 m spatial resolution were retrieved from the National Aeronautics and Space Agency (NASA) using Google Earth Engine (GEE). MODIS imagery is preferred as a data source over Landsat imagery because of the availability of a sufficient number of images at regular intervals of time, its strong correlation with changes in vegetation biomass because of higher temporal resolution, and its relatively cloud free temporal signal [46].

The MODIS NDVI product employs a maximum NDVI value compositing technique, which selects the most representative value for each pixel during a 16 day period [47]. This approach offers a significant advantage in reducing the effect of clouds on the NDVI product, particularly during summer season in the study area. MODIS data are effective for monitoring human-driven vegetation changes aimed at ensuring sustainable land management that requires the localized implementation of best management practices [48]. The time series spans from February 2000 to December 2020 with a 16-day interval, resulting in twenty-three images for each year except 2000 because of data inaccessibility for the first three acquisition time intervals.

Data quality flags from MOD13Q1 were used to identify and remove low quality pixels from the data, interpolate data gaps, and smooth the images using an adaptive Savitzky–Golay filter series [49]. All images were reprojected to the WGS 84/UTM zone 37 N and spatially fitted to the extent of the study area shapefile using ArcGIS 10.8.

The NDVI time series was extracted from the MOD13Q1 Vegetation Index product. MOD13Q1 product provides an NDVI layer calculated from the reflectance values of the red (R) and near-infrared (NIR) spectral bands [50] and is correlated with the photosynthetic activity of green vegetation [51].

$$NDVI = \frac{NIR - R}{NIR + R}$$

The NDVI value ranges from -1 to 1, where higher values indicate healthier and denser vegetation. Values lower than 0.1 represent bare areas of soil, rock, or snow [52]. This vegetation index has the advantage of minimizing noise in the imagery from the difference in solar illumination and cloud shadows [53]. Nevertheless, in regions characterized by high biomass, such as the Amazon, the NDVI may approach saturation asymptotically [54].

8.2.3 Seasonal Change Detection

Seasonal changes in vegetation have been monitored using various methods [23]. TIMESAT 3.3 is a widely used program designed primarily to the process products of satellite spectral measurements, such as vegetation index time series [49]. This algorithm boasts the ability to rectify errors and enhance data quality using the Savitzky–Golay (SG) adaptive filtering method [55], which effectively eliminates spikes, noise, and irregularities stemming from factors like clouds and weather conditions. Moreover, TIMESAT enables the exploration and extraction of seasonality parameters from NDVI time series data and then characterizes the vegetation responses. Compared to the other two curve-fitting algorithms in TIMESAT (double logistic and asymmetric Gaussian), the SG algorithm has a high fitting accuracy [56] because it maintains the width and shape of the original signal while filtering the noise [57] and providing more accurate seasonal parameters [58]. It is effective for NDVI data and can manage complex behaviors, such as a rapid increase followed by a decreasing plateau [55]. The SG filtering calculation formula is shown in Equation (2) [59]:

$$Y_j = \sum_{i=-n}^{i=n} \frac{c_i Y_j + i}{N}$$

where Y_j is the reconstructed NDVI value, $Y_j + i$ is the original NDVI value, c_i is the coefficient obtained via SG filtering, and N is the smoothing window size.

The seasonal parameters of the vegetation from the NDVI time series were calculated using linear regression Equation (3), as follows [59]:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times P_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} P_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}$$

where *Slope* represents the trend change, P_i is the seasonal parameter value for the i year, and n is the length of the time series. If the *Slope* > 0, the seasonal parameter is increasing; if the *Slope* < 0, the seasonal parameter is decreasing; and if the *Slope* $= 0$, the seasonal parameter remains unchanged.

TIMESAT employs a computationally simple and robust threshold method to identify the beginning and end of growing seasons [60]. A threshold value of 25% seasonal amplitude is defined for both the start and end dates of the season, which are the threshold distances from the left minima and right maxima of the seasonal curve, respectively. The threshold value was chosen from the TIMESAT graphical user interface in MATLAB after inspecting the seasonality parameter values and graphs of the time series curves for different thresholds in different vegetation covers of the study area. To sample the study area, known locations were identified for each vegetation type, avoiding mixed or heterogeneous representations. The seasonal parameters extracted from TIMESAT are the

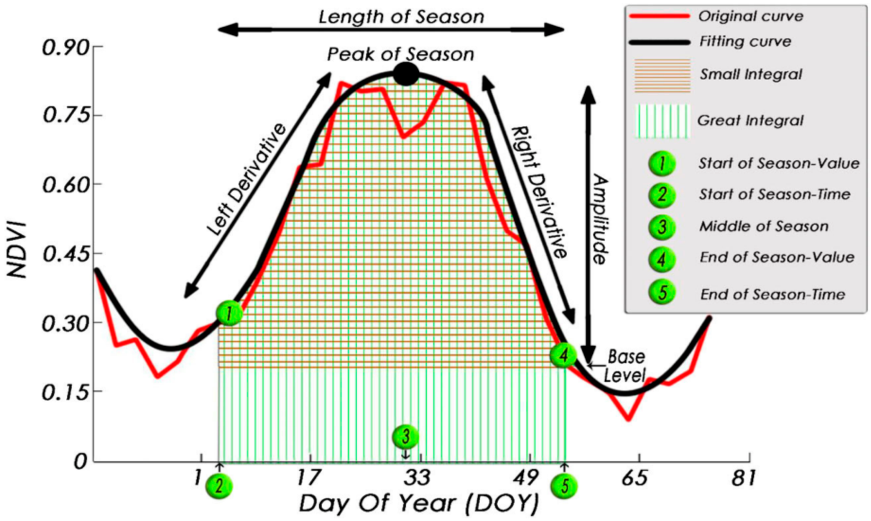

Figure 8.2: All seasonal parameters can be extracted using the TIMESAT algorithm [62]

start of the season (SOS), signifying an upward trend at a 25% threshold in the NDVI time series due to photosynthesis activities in the vegetation; the end of the season (EOS), denoting a downward trend at a 25% threshold in the NDVI time series; and the length of the season (LOS), representing the duration between the SOS and EOS. Collectively, these parameters are referred to as phenological indicators.

The seasonal changes in vegetation were also described using the following ecosystem condition indicators: peak value (PV), the maximum value of the NDVI during the season; base value (BV), the average between the left and right minima values; seasonal amplitude (Amp), the difference between PV and BV; large seasonal integral (LI), the integral of the fitted function describing the season and the zero level from the SOS to EOS, which is an estimate of the annual vegetation productivity; and small seasonal integral (SI), the integral of the difference between the fitted function describing the season and the BV from the SOS to EOS (Figure 8.2). LI has the biological significance of expressing the relative amount of vegetation biomass within a given season, while SI holds biological significance by expressing the relative amount of vegetation biomass within a given season above the base level [61]. The correlation between the seasons of the study period detected by TIMESAT and the above parameters was calculated to explore the trajectories of each parameter and to link them with ecosystem conditions in response to vegetation changes. The total number of seasons detected by TIMESAT based on the supplied NDVI was twenty (n − 1, where n is the number of years) [49].

8.2.4 Interannual Trend Changes

The interannual NDVI trends with the number of breakpoints in the time series, magnitude, and direction of changes were extracted using the Break Detection For Additive Season and Trend (BFAST) algorithm. BFAST is an iterative algorithm that decomposes time series data into three components: trend (frequency variation in pixels), seasonal (variation in seasonal frequency), and remainder (the remaining variation from the sensing environment) [20]. The decomposition algorithm is as follows:

$$Y_t = T_t + S_t + e_t \quad (t = 1, \ldots, p)$$

where Y_t is the observed data at time t. T_t, S_t, and e_t are the trend, seasonal, and remainder components at time t. p represents the number of observations. T_t is fitted with linear piecewise models with specific intercepts α_i and slopes β_i on different $m + 1$ segments, as in the following equation:

$$T_t = \alpha_i + \beta_i t \qquad (t_{i-1} < t \leq t_i, i = 1, \ldots, m)$$

where t_i is the time at breakpoint i and m is the number of breakpoints in the trend component.

The BFAST breakpoints refer to an abrupt change in the NDVI, while the NDVI time series trend is different on opposite sides of the breakpoint [41]. The magnitude and direction of abrupt changes are derived using the intercept α_i and slope β_i of consecutive linear models. Magnitude is the difference, T_t, between t_{i-1} and t_i, and is calculated as follows:

$$Magnitude = (\alpha_{i-1} - \alpha_i) + (\beta_{i-1} - \beta_i)\, t$$

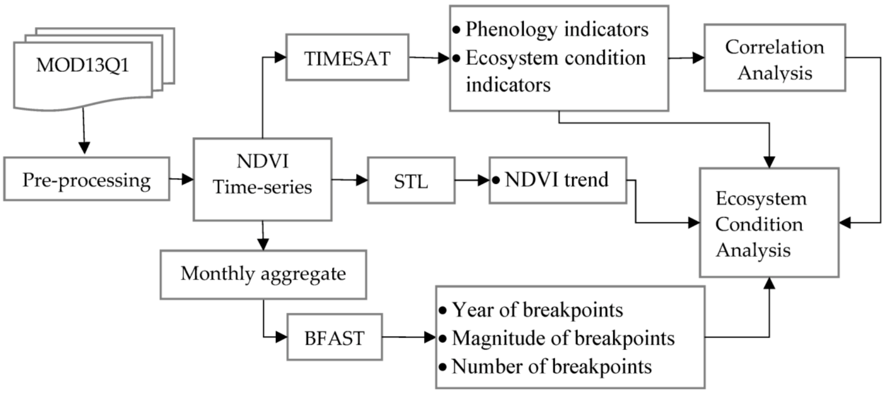

Figure 8.3: The general workflow of vegetation seasonal and interannual change detection for ecosystem condition analysis.

The BFAST algorithm was applied for all pixels in the study area through the bfast package [63] using R program version 4.2.2. The irregular time series were extracted, transformed into daily time series, and finally to monthly time series [64]. BFAST was run using the dummy model that focuses on trend change detection rather than temporal shifts in land surface phenology. The seasonal component was derived using this model to track the variations in the trend component [65]. For parameter h, we used 1/20 evaluating several values, considering that plantation activities in the study area commenced affecting the vegetation status during the second half of the study period. Additionally, we considered the primary tasks undertaken by the community related to plantation, including activities, such as establishment and harvesting. The interannual changes in direction and magnitude of breakpoints before and after plantation practice were used to analyze the ecosystem condition.

Moreover, the NDVI time series were decomposed using the STL package in R, and the trend component was used to show the rate and direction of the average change in vegetation for the period 2000–2020 and the possible implications for the condition of the ecosystem. The general methodological workflow is depicted in Figure 8.3 below.

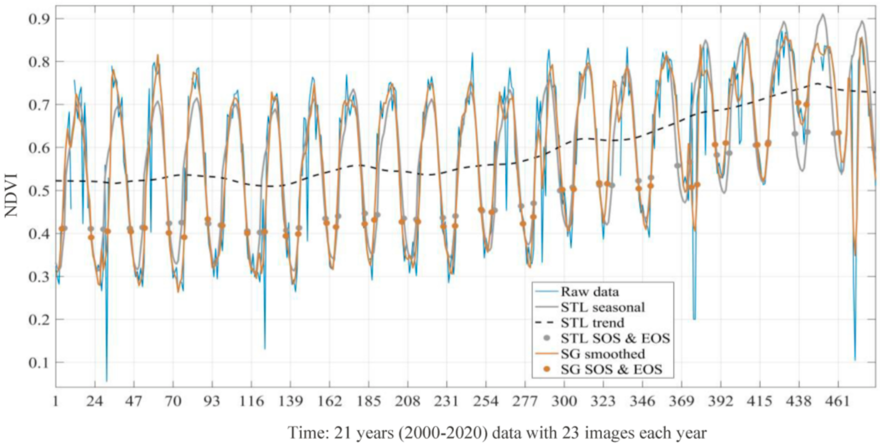

Figure 8.4: NDVI raw, SG smoothed, and STL decomposed data for Acacia decurrens plantation forest.

8.3 Results

8.3.1 Seasonal Changes

Indicators of seasonal changes in the annual cycle of the NDVI were extracted for the identified vegetation types using TIMESAT. In vegetated areas with similar vegetation types and homogeneous compositions, monitoring indicators of seasonal change using satellite NDVI can prevent the effects of various ground-based observation noises [66]. For each vegetation type, the average value of all identified parameters was calculated from 2000 to 2020. The NDVI value of the study area showed an increase throughout the study period, with variation from season to season observed for most types of vegetation. In Figure 8.4, the sample pixel (latitude: 11.0453°N, longitude: 36.8631°E) representing an Acacia decurrens plantation in the central part of the study area shows the harmonic model fitted to the NDVI raw values and SG smoothed data across the study period. The trend decomposition of the NDVI shows that there was a remarkable increase, especially starting around 2010 (Figure 8.4).

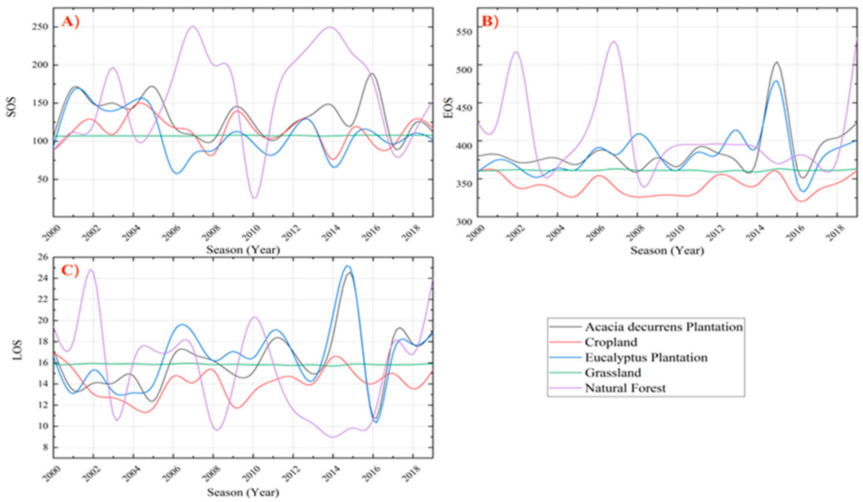

Figure 8.5: The phenology indicators extracted from TIMESAT: (A) the start of the season (SOS); (B) the end of season (EOS); (C) the length of season (LOS). SOS and EOS are expressed in days of the year (DOY), and LOS in 16 days.

8.4 Results

Seasonal parameter values were extracted for the phenology indicators SOS, EOS, and LOS and the ecosystem condition indicators PV, BV, Amp, LI, and SI for distinct types of vegetation: natural forest, Acacia decurrens plantation forest, Eucalyptus plantation forest, grassland, and croplands. The results reveal specific variations in the patterns of the vegetation type responses across the study period. Cropland and plantation forests showed a relatively similar pattern for SOS and EOS. Grasslands showed slight variation throughout the study period for all phenological indicators. The earliest and latest growing events were recorded in natural forests, but the changes from year to year were relatively gradual (Figure 5A). Croplands were the first to be identified by EOS across the entire study period (Figure 8.5B).

The phenology indicator parameters are shown in Figure 8.6 using error bar plots, sorted based on the mean values from the largest number of days to fewest.

For most of the vegetation in the study area, the SOS occurs in April,

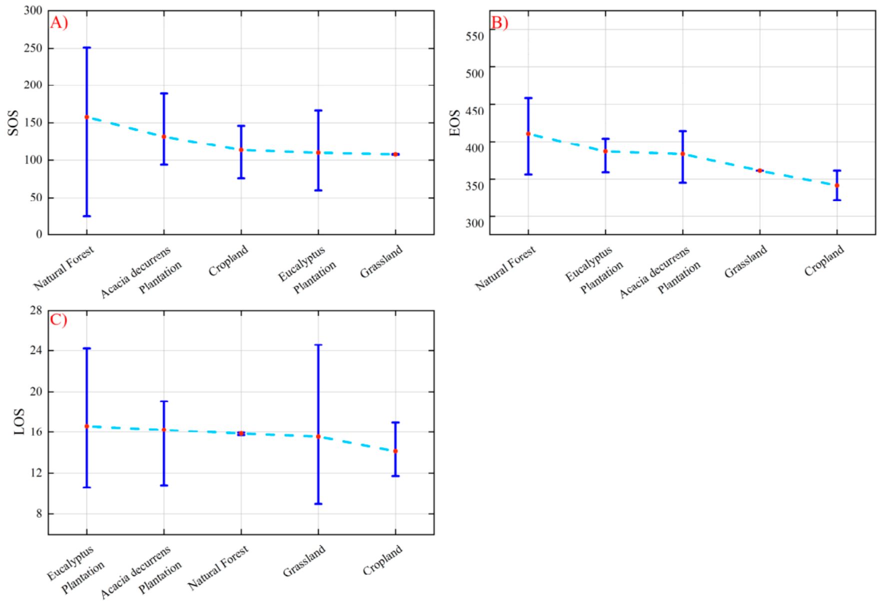

Figure 8.6: Error bar plot for phenology indicators: (A) SOS, (B) EOS, and (C) LOS. Vegetation types were sorted based on the mean values of each parameter, from highest to lowest

May and June, while the EOS is observed from November to February (Figure 8.7).

The ecosystem status indicator parameters showed that the natural forest had the highest values of PV and BV and the lowest values of Amp and SI across the entire period (Figure 8). The patterns of Acacia decurrens and Eucalyptus plantation forests were relatively similar for most parameters. For example, the PV, BV, and LI of Acacia decurrens and Eucalyptus plantation forests increased during the study period, while the Amp and SI values decreased (Figure 8). The grassland pattern remained without noticeable variations in Amp and SI, similar to the phenology indicator parameters (Figure 8.8C,E).

The ecosystem condition indicator parameters are displayed in Figure 8.9 using error bar plots, sorted based on the mean values from the highest value to smallest.

The correlation values of SOS were below 0.2 for all vegetation types. EOS and LOS did not show significant changes for any vegetation type during the study period either. Acacia decurrens (0.97), Eucalyptus

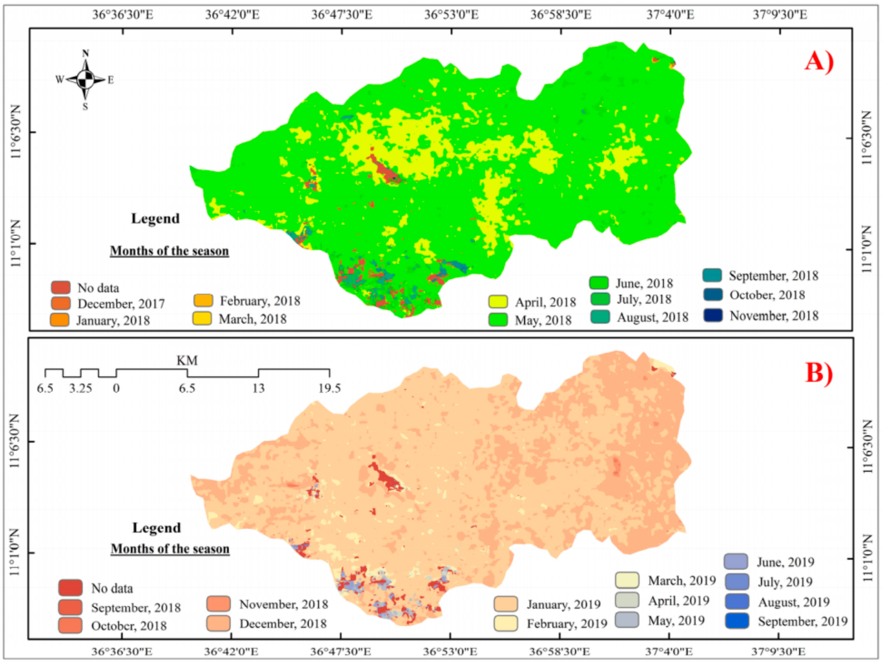

Figure 8.7: SOS (A) and EOS (B) months in Fagita Lekoma District in 2018.

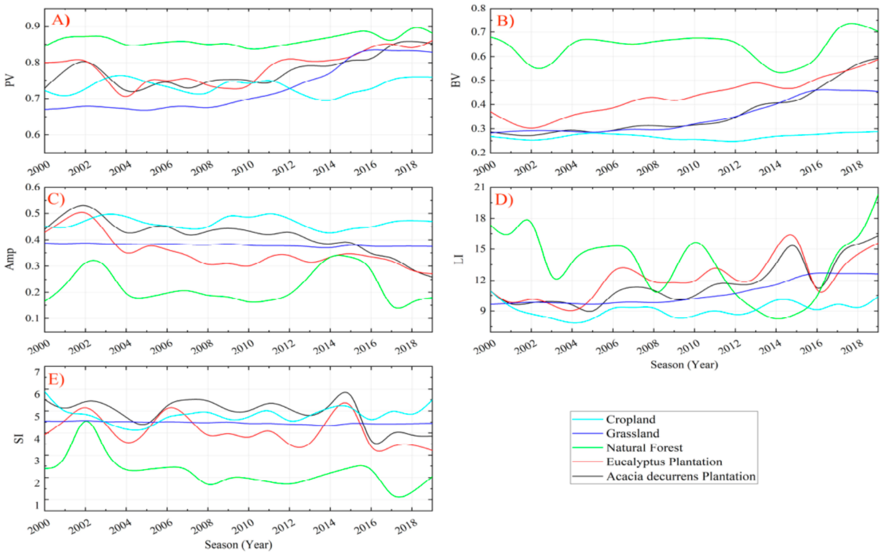

Figure 8.8: Ecosystem condition indicators extracted from TIMESAT: (A) peak value (PV), (B) base value (BV), (C) amplitude (Amp), (D) large integral (LI), and (E) small integral (SI).

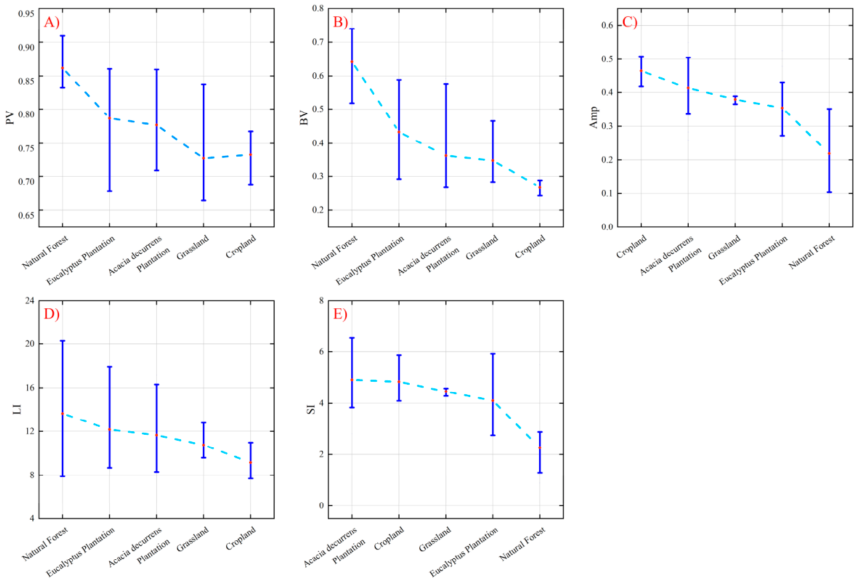

Figure 8.9: Error bar plot of ecosystem condition indicators: (A) PV, (B) BV, (C) Amp, (D) LI, and (E) SI.

(0.95), and grassland (0.91) showed a higher correlation than the other vegetation types based on PV. Croplands and natural forests exhibited relatively low changes across the study seasons in terms of BV, Amp, and LI (Table 8.1).

8.4.1 Interannual Changes

The BFAST algorithm was run for all NDVI pixels for the entire period to extract the year of the largest breakpoint, the magnitude of change for

Vegetation Types	**Phenology Indicators**			**Ecosystem Condition Indicators**				
	SOS	**EOS**	**LOS**	**PV**	**BV**	**Amp**	**LI**	**SI**
Acacia decurrens Plantation	0.016	0.32	0.256382	0.971338	0.927024	−0.9298	0.674328	−0.49035
Eucalyptus Plantation	0.034	0.12	0.369648	0.951077	0.554967	−0.73172	0.621987	−0.3359
Natural Forest	0.178	−0.14	−0.22337	0.14324	0.363887	−0.02876	−0.23459	−0.50731
Grassland	0.071	0.03	−0.38195	0.917557	0.902911	−0.73747	0.907974	−0.69206
Cropland	−0.15	−0.03	0.181415	0.361984	0.116899	−0.07865	0.233017	0.123548

Table 8.1: Correlation coefficients of seasons during the study period and seasonality parameter values.

the largest breakpoint, and the number of breakpoints in each pixel. The magnitude and number of breakpoints in vegetation indicate the ecosystem condition and stability status, respectively. Most of the study areas (63.32% of the total) experienced breakpoints. The spatial distribution and area percentage of the largest breakpoints in all pixels for each year are shown in Figure 8.10(A,D), respectively. The results show that the highest percentage of breakpoints occurred in 2015 (24.7%), 2012 (18.6%), and 2014 (9.8%). By contrast, the lowest percentage of breakpoints was observed in 2004 (0.1%), 2007 (0.2%), and 2005 (0.5%).

The magnitude and direction (positive changes or increasing NDVI trends and negative changes or decreasing NDVI trends) of the breakpoints for the time series data are shown in Figure 8.10(B,E). The magnitude of the annual change varied from -0.54 to 0.38. The observed changes between -0.2 and 0.2 accounted for 93% of the area. The frequencies of magnitudes with values near zero were relatively high.

The number of largest breakpoints detected in the NDVI for each pixel varied from one to seven. Approximately 38.08% of the districts had one breakpoint, 15.47% had two breakpoints, 6.83% had three breakpoints, and 2.28% had four breakpoints. Areas with five, six, and seven breakpoints represented only 0.76% of the study area (Figure 8.10C,F).

8.5 Discussion

This study investigated the potential of using NDVI time series data to track and interpret local level vegetation trends following plantation practices in the Northwestern Highlands of Ethiopia. The NDVI value of the study area exhibited a typical increase, which was characterized by seasonal and interannual vegetation changes. Our findings demonstrate that these changes can be exploited using satellite time series images to analyze vegetation trends and their implications for ecosystem conditions. These techniques can be used to monitor vegetation trends across decades, depending on the availability of satellite data and plantation types. The findings presented here hold promise for their use in identifying differ-

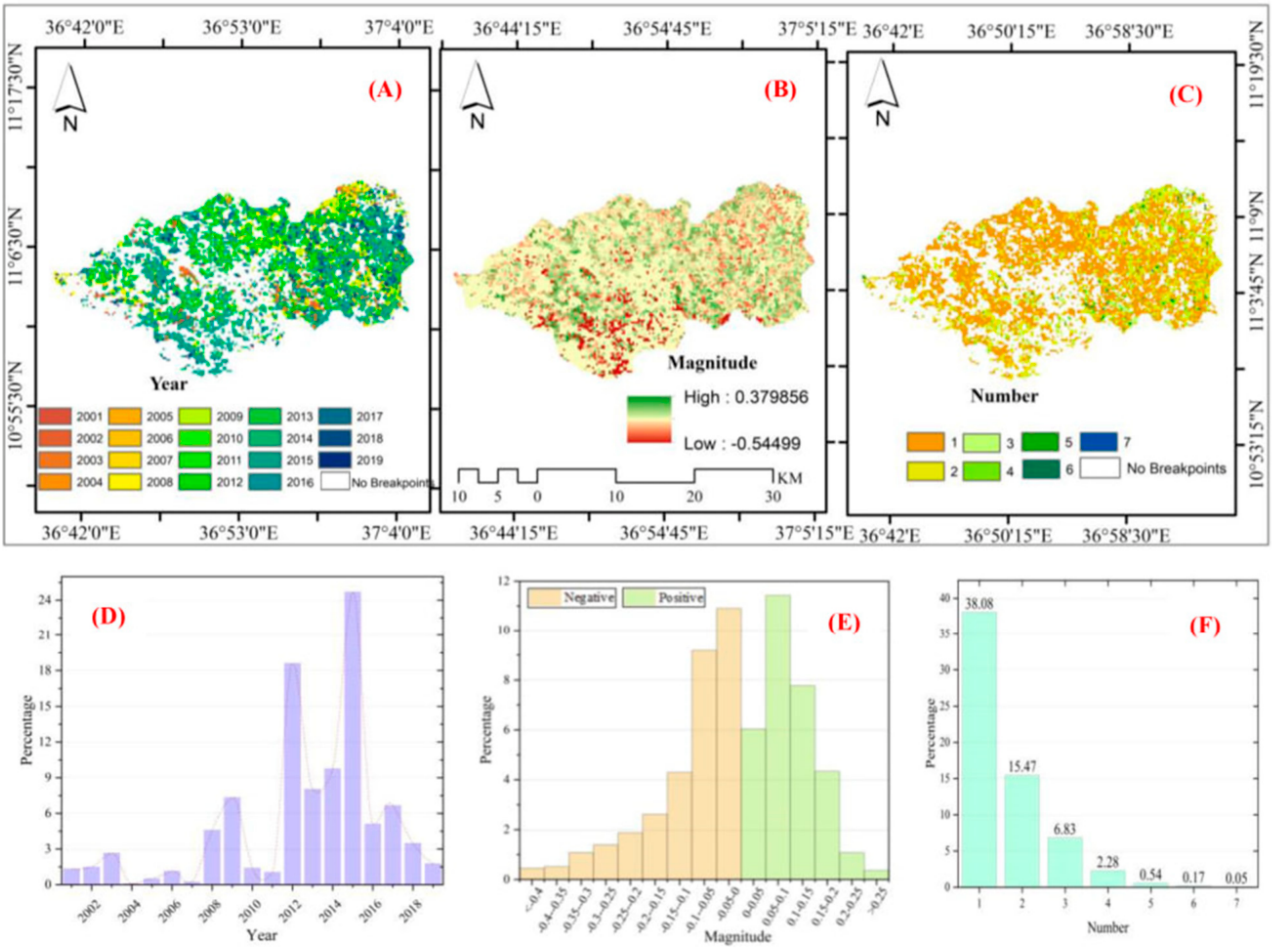

Figure 8.10: Interannual changes detected using the BFAST algorithm from the NDVI time series data: (A) spatial distribution of the year of largest change; (B) spatial distribution of the magnitude of change; (C) spatial distribution of the number of changes; (D) area percentage of the year of largest change; (E) area percentage of the magnitude of change; and (F) area percentage of the number of changes.

ent parameter trajectories for vegetation types and their implications for ecosystem conditions. The ability of forest managers to assess ecosystem conditions following plantation practices can inform and optimize restoration strategies.

8.5.1 Seasonal Changes

The SG algorithm in TIMESAT revealed that the SOS for most vegetation in the study area was May and June. This is when most of the highlands of the country, including the study area, start receiving rainfall [35]. Throughout the study period, the order of growth initiation was as follows: grasslands followed by Eucalyptus plantation forests, croplands, and Acacia decurrens plantations. Grasslands begin to grow early and are relatively sensitive to weather conditions. Natural forests begin growing late, mostly in mid June, and some of them did not show growth within the specified threshold, which may have been due to the maturity stage of vegetation (Figure 8.5A). This might be the reason that remotely sensed NDVI time series have difficulty detecting phenological changes in evergreen forests, because the NDVI tends to be saturated in areas with large amounts of biomass, such evergreen forests [54].

The average EOS for croplands and grasslands was December, which is the start of the winter (dry) season. Among the identified vegetation types, EOS starts early on croplands, and this is due to most of the crops in the study area being annual crops that are harvested mostly in the months of December and January. In contrast, January was the EOS time for Acacia decurrens and Eucalyptus plantations during the study period. Natural forests stopped growing around February, which is relatively late compared to other vegetation types. The eastern part of the study area began the EOS earlier (Figure 8.6B). Some natural forests in the southwestern part of the study area had an EOS that continued to the next season, extending the growing period for more than one natural year. Evergreen forests lack a distinct seasonal cycle in the NDVI [67]. The average LOS in the last two decades was highest for Eucalyptus plantations (8.85 months) followed by Acacia decurrens plantations, grasslands, natural forests, and croplands (8.65, 8.45, 8.29, and 7.56 months), respectively. Between the first half (2000–2009) and the second half (2010–2020) of the study period, there was a significant increase in LOS for Acacia decurrens and Eucalyptus plantations from 8.03 months to 9.27 months, and 8.85 to 9.36 months, respectively. The LOS in the first half for both plantations was relatively similar to that of grasslands and croplands, which implies that before the practice of plantations, the land was covered by grasslands and croplands (Appendix Figure A1). This result complements the findings of previous studies conducted in the study area [34], which found that, before the establishment of plantation forests, the district was predominantly covered with croplands and grasslands. The LOS of natural forests showed a slight decrease between the two decades from 8.78 to 7.8 months. Unlike for the other vegetation types, for natural forests, a seasonal cycle takes a relatively prolonged time, which might be related to the maturity level of the forests and their year of establishment (Figure 8.5). Most vegetation types did not show significant differences in the values of phenology indicators before and after the plantation developed, and this result is in line with the findings of Sharma [68], which showed that there was no significant difference in phenology parameters between protected and unprotected areas.

As shown in Figure 8.8A,B, there was a marked increase in PV and BV starting around 2010 for the Acacia decurrens plantation, Eucalyptus plantation, and grasslands. However, the PV and BV of croplands and natural forests remained relatively stable, with almost the same values (Figure 8.8). On the other hand, the Amp and SI of both plantations declined due to a positive change in BV, which implies an increase in green vegetation. The SI of evergreen vegetation may be small even if the total productivity of the vegetation is high [69]. The LI showed a relatively higher increase in the second half of the study period for the Acacia decurrens and Eucalyptus plantations. A relatively slight increase was also observed in grasslands and croplands, and a slight decline was recorded in natural forests. The LI value of plantations in recent years has been increasing, and the SI value has decreased, indicating that the ecosystem is highly productive with dense evergreen vegetation [70]. The presence of a homogenous and young canopy with a fast growing nature and high stand density indicates a higher biomass expansion [70].

Seasonal Parameter Value Distribution for Vegetation Types

The phenology indicators are shown in Figure 8.6, using error bar plots, which were sorted according to the mean values, from a larger number of days to fewer. The mean value of SOS was earliest in grasslands, and this proves that grasses were highly responsive to spring rains. In other ways, natural forests require a relatively long time to show growth following the change in season. The EOS of cropland appears earlier, and the EOS of natural forest appears the latest. The observed range of EOS was between 322 and 536. Eucalyptus plantation forests have the largest mean value, which indicates the quality of the species' ability to continue growing, even in dry months, by extracting underground water using its deep roots. This can be attributed to the fact that the roots of Eucalyptus are long, can grow up to 20–30 feet, and extract more water from the deepest parts of the soil [71]. Cropland exhibited the lowest mean LOS value because the crops were harvested approximately five months after planting. The LOS range for all vegetation types was 8.96 and 24.57, both recorded for natural forests in the 14th and 3rd seasons of the time series, respectively.

Natural forests had the highest mean PV because dense forests in the study area are green almost all days of the year and have higher NDVI values. The mean PV value of the croplands was the lowest (Figure 8.9A), suggesting that the crops remained green for some months of the year and that after harvest, the area could be bare land. The order of vegetation types based on PV and BV was the same (Figure 8.9A,B), which shows the existence of a strong relationship between the parameters. PV and BV values were high, especially in the last few years of the study period, for most of the vegetation types. These parameters are best for distinguishing the productivity level of vegetation classes, where higher NDVI values correspond to vegetation in ecosystems under recovery [72]. Unlike the PV values, croplands and natural forests had the highest and lowest mean Amp, respectively (Figure 8.9C). Grasslands and natural forests had the narrowest and widest Amp ranges, with values between 0.365 and 0.389 and 0.103 and 0.351, respectively. A narrow Amp is characteristic of mature forests [73]. Generally, increasing trends in PV and BV and decreasing trends in Amp values were observed for most vegetation types. These results are consistent with the findings of Leeuwen [74], who assessed the vegetation condition in a restored forest at risk of wildfire.

Natural forests had the highest mean LI, followed by Eucalyptus and Acacia decurrens plantations (Figure 8.9D). In terms of the mean SI value, Acacia decurrens had the highest and natural forests had the lowest. The range of SI values for both plantations was relatively wider than that for other vegetation types, which shows the significant effect of plantation practices on NDVI values (Figure 8.9E). According to the ecosystem condition indicator parameters, the order of vegetation types is the same for PV, BV, and LI. Likewise, Amp and SI also had a relatively similar order of vegetation types. The Amp and SI of grasslands did not show significant differences, indicating consistency for most of the parameters.

Correlation between Seasons and Seasonality Parameters

For phenology indicators, the correlation coefficient of SOS was higher than that of EOS in natural forests, grasslands, and croplands. The EOS correlation was higher than that of SOS and LOS for the Acacia decurrens plantation. This might be because the greenness of the plantation forests in the study area was relatively less affected by the beginning of the rainfall. The correlation of PV was higher than that of Amp for all vegetation types. Amp decreased for all vegetation types, which correlated with an increase in the minimum seasonal NDVI rather than a decrease in the maximum NDVI. A reduction in Amp is an indicator of improved vegetation growth [60]. The Acacia decurrens plantation has the highest correlation of Amp, followed by the Eucalyptus plantation and grassland. In contrast, the lowest growth rate was observed in natural forests. The PV was higher than the BV for all vegetation types, except for natural forests. Among the other indicators of ecosystem conditions, the correlation of LI was higher than that of SI in vegetation types. This indicates that there were differences in these two ecosystem condition indicators before and after the plantation was established because of the difference in aboveground primary productivity. Land use activities, such as conservation measures, have significant positive effects on LI and SI values [68].

8.5.2 Interannual Changes Analysis

Breakpoints provide evidence of the statistical significance of variations in NDVI values. Thus, when a breakpoint emerges, it indicates a substantial shift in NDVI values that cannot be statistically attributed to preceding periodic or linear trends [75]. This may be related to disruptions in anthropogenic or environmental factors [76]. For instance, negative breakpoints correspond to periods associated with drought, flooding, and fire events [77]. Most of the breakpoints occurred during the early years of the study period and corresponded with natural forests and wetlands, which implies the existence of deforestation activities at the time and the drying out of water logged areas. The percentage of wetland cover in the area also shrank from 18.58% in 1973 to 0.2% in 2015 [34]. During the first half of the study period, the forest cover in the study area decreased, mainly due to population growth and related effects, such as increased demand for arable land, fuelwood, and construction wood [35]. The magnitude map (Figure 8.10B) also confirms that the southern parts of the study area, where natural forests are found, exhibited relatively extreme negative values. The largest area percentage of breakpoints was detected during 2015, and this value agrees with the TIMESAT result. The highest abrupt change in vegetation during 2015 caused a decrease in LI in plantations in 2016 (Figure 8.8D), which was highly correlated with plantation activities. Plantation practices may result in the detection of two breakpoints from a single pixel: during the greening period and after harvest. The effect seen in 2015 (BFAST) and 2016 (TIMESAT) might have been due to the harvest of more plantations for charcoal production. Farmers usually harvest plantations after four years and above to generate income [78].

Alternatively, positive peaks in the breakpoints are related to the practices of afforestation, ecological restoration, and policy driven land use conversions [76]. The breakpoints that happened in the second half of the study period were more intense, and this attributed to the expansion of plantation forests in the area. The results are consistent with the findings of Wondie and Mekuria [35], who demonstrated that the forest cover of Fagita Lekoma District increased by 5.2% between 2010 and 2015, from 11,397 ha to 17,330 ha. The area coverage of Acacia decurrens plantations has progressively increased since 2006 in the Guder watershed, which is one of the watersheds found in the district. The study by Birhan et al. [79] in the same watershed showed that between 2006 and 2017, a remarkable amount of land use/land cover was converted to plantation forests from cropland and grazing land, so the forest cover of the watershed increased by more than 400%. The forest cover of Fagita Lekoma District expanded by 1.2% per year between 1995 and 2015, mainly due to the planting of Acacia decurrens at the expense of cultivated land, which decreased by 1% per year [35]. The soil in Fagita Lekoma District is highly acidic [45], which is attributed to heavy rain and results in low crop productivity. This was one of the main driving factors that promoted the expansion of Acacia decurrens plantations in the district over the past few decades because this species has a leguminous character, which enables it to reduce soil acidity [80].

The spatial distribution of breakpoints that occurred in the natural forest during the early years of the study period shifted to other types of vegetation in the later years in various parts of the study area (Figure 8.10A). The findings of Belayneh et al. [37] also confirmed that the expansion of Acacia decurrens plantation forests in the study area reduced human and livestock pressure on natural forests by prioritizing firewood and reducing free grazing. Acacia decurrens plantation forest cover progressively increased across the district by 16% between 2000 and 2017 [38]. These changes in land use have enhanced vegetation regeneration and significantly altered the dynamics of vegetation status in the area. This might be related to the potential of Acacia decurrens in terms of soil erosion reduction and the recovery of soil fertility [80]. Moreover, Acacia decurrens serves a dual purpose by alleviating pressure on the natural forest, which has been suffering from a high rate of forest degradation due to the collection of fuelwoods and the production of charcoal, and by serving as an alternative land use that is more economically lucrative [81].

In the study area, apart from protected natural forests and some irrigated croplands, most of the land experienced at least one abrupt change in the NDVI between 2000 and 2020. The number of breakpoints was mostly linked to the establishment and harvesting of Acacia decurrens plantations. The spatial distribution map of the number of changes detected in the NDVI is shown in Figure 10C, where more than half of the district (53.55%) had one or two breakpoints. Most of the areas with frequent breakpoints were unevenly distributed in various parts of the study area and characterized by the early adoption of Acacia decurrens plantations.

8.5.3 Implications for the Ecosystem Condition

Fagita Lekoma District has degraded soils due to its large population density and higher rainfall distribution [82], in addition to continuous cultivation of the land for longer periods [43], as well as extensive deforestation that resulted in acidic soils of low fertility [83]. Programs implemented by the local and national government focused on the regeneration of the ecosystem may have produced a positive change in the condition of the vegetation [76]. The Acacia decurrens plantation has been promoted by both government and nongovernmental organizations because this species thrives on degraded lands, including gullies.

The trend component of the NDVI in the study area increased from year to year during the study period (Figure 8.11). The mean NDVI of the entire study area at the beginning and in the final years of the study period differed, which confirms how the high vegetation cover of the district has expanded. The five-years mean NDVI, which was 0.58 for the years 2000–2004, rose to 0.65 during 2015 and 2020. Such a positive change in the NDVI has shown implications for the productivity of the land and indicates the existence of changes in the overall ecological pattern [84]. A study by Mola and Linger [85] reported that there has been an improvement in soil fertility on land parcels covered by Acacia decurrens plantation forests. These results are consistent with another study conducted in the study area that also confirms that the expansion of Acacia decurrens plantations has affected the soil's physical and chemical properties. For instance, the total nitrogen of the soil under Acacia decurrens plantations is 43.5% higher than that under cropland [79]. Likewise, the pH value of the soil under an Acacia decurrens plantation is 2% lower than the soil under cropland, whereas the availability of phosphorus in Acacia decurrens plantation soil is 1.25 mg kg−1 lower than that in cropland soil [79]. The degraded soils of the district have been considerably improved, mainly through the planting of Acacia decurrens and enhanced natural capital [83], and the ecosystem service value increased by 54% from 2006 to 2017 [36]. Acacia decurrens plantations are typical biological measures for the restoration of highly degraded land and improving resilience to climate shocks [86].

The TIMESAT results for ecosystem condition indicators (Figure 8.8) show that there was a significant change in most parameters within the identified study period. For example, the PV, BV, and LI increased, especially for Acacia decurrens plantations, Eucalyptus plantations, and grassland. These indicators account for the most substantial variations and exhibit strong correlations with the presence of vegetation cover [87].

The Amp and SI for most of the vegetation types were characterized by negative changes due to the increase in the BV, which is an indicator of stable vegetation condition and the restoration of the ecosystem. Lower values of SI and higher values of LI imply that the vegetation under consideration is a highly productive ecosystem with dense canopy cover [70]. The growth of the relative amount of vegetation biomass is an indicator of gradual ecosystem restoration [41].

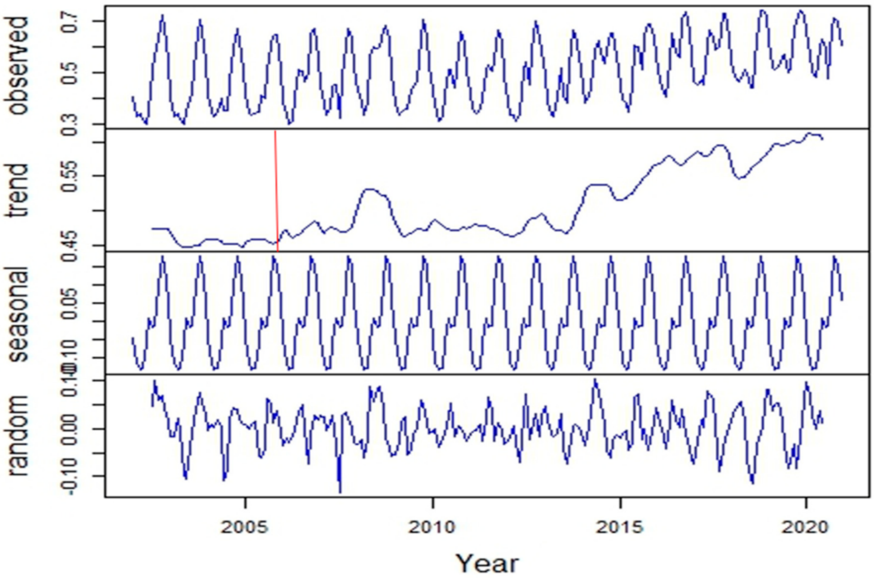

Figure 8.11: The decomposed NDVI time series of the entire study area during 2000—2020 (the red line from the graph indicates the relative time when the NDVI trend started to rise).

The BFAST results also confirm that there was a change in the ecosystem in terms of the magnitude and number of breakpoints during the study period. The study area exhibited breakpoints for the identified years at different percentages (Figure 8.10A,D). Changes at the beginning of the study period were mostly characterized by a negative magnitude. Before the start of the plantation practice, the forest cover was diminishing in the district [79] due to population growth and related effects, such as increased demand for arable land, fuelwood, and construction wood [35]. However, around 2010, positive changes dominated, and around half of the area with abrupt changes was characterized by positive changes. This finding is in line with that of Wondie and Mekuria [35], who reported that forest cover has increased since 2010 because of the expansion of Acacia decurrens plantations. The forest cover of the district has shown an upward trend over the last two decades because of Acacia decurrens plantations and the regeneration of previously degraded natural forests because of a reduction in the normal pressure on natural forests achieved through the replacement of fuelwood and construction materials [37]. The expansion of Acacia decurrens plantation forest plays a vital role in biophysical environment rehabilitation and conservation [38]. As a result, more than 30% of the study area exhibited a positive breakpoint magnitude during the study period, and approximately 36% remained without abrupt changes. The negative changes experienced in recent years are related to the harvesting of plantations that the community replants immediately after.

In general, the analysis in this study shows that seasonal and interannual changes enable the inference of changes in the ecosystem. Both the TIMESAT and BFAST outputs, along with the increasing trend of the average NDVI, indicate significant vegetation regeneration, serving as significant indicators of ecosystem restoration.

8.5.4 Conclusion

Changes in seasonal and interannual vegetation trends play a significant role in determining the condition of an ecosystem. Plantation-mediated shifts in seasonal and interannual vegetation changes underscore the importance of identifying parameters and methods for analyzing ecosystem conditions. In line with our objectives, we conducted a study in the Northwestern Highlands of Ethiopia focused on utilizing NDVI time series data to monitor and interpret local level vegetation trends, especially following plantation practices. The findings and implications of this research provide valuable insights into the dynamics of vegetation and ecosystem conditions in the area.

The spatiotemporal behavior of most types of vegetation showed that in the study area, vegetation changes in the last two decades have had a more pronounced effect on ecosystem condition indicators than on phenology indicators. Breakpoints in NDVI data highlighted significant shifts in vegetation cover. Negative breakpoints during the early years of the study period were associated with deforestation. Most of the largest breakpoints were detected during the second half of the study period and were linked to afforestation and land use conversions, primarily due to the expansion of Acacia decurrens plantation practices. Positive changes in NDVI trends suggest an improvement in ecosystem condition, particularly in vegetation cover and productivity. The findings of applied data decomposition algorithms have significant implications for ecosystem restoration and conservation efforts in the study area. The promotion of plantation practices, particularly Acacia decurrens, has positively impacted vegetation regeneration, contributing to improved ecosystem health.

Overall, the study demonstrates that the adoption of afforestation practices, such as the cultivation of Acacia decurrens plantation forests, has led to positive changes in ecosystem conditions in Fagita Lekoma District. These findings provide valuable guidance for land use planning, conservation, and sustainable ecosystem management in regions facing challenges like soil degradation and deforestation. The study highlights the potential of leveraging remote sensing data to monitor and manage ecosystems effectively over time, contributing to ecological resilience and improved environmental conditions in the study area.

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Chapter 8

Appendix

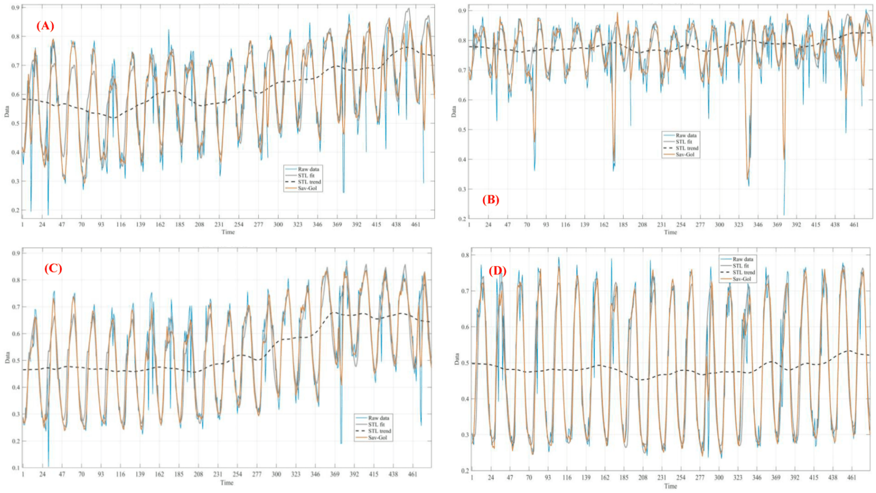


Figure 8.12: Appendix A1. NDVI data decomposed results using TIMESAT for the identified vegetation types in the study area: (A) Eucalyptus plantation forest, (B) natural forest, (C) grassland, and (D) cropland.

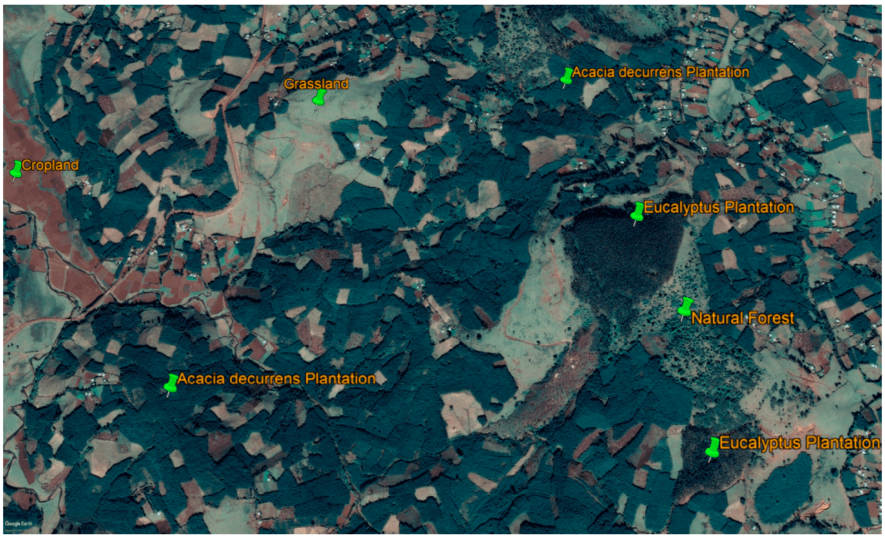
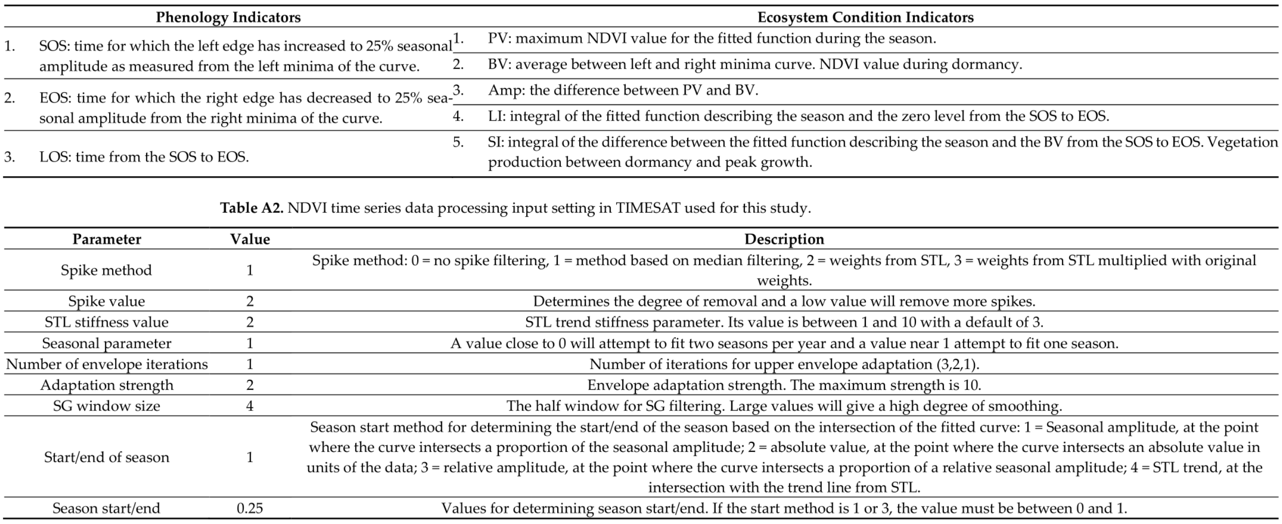


Figure 8.13: Appendix A2. Vegetation types considered for TIMESAT in the study area (Google Earth image).



Phenology Indicators	Ecosystem Condition Indicators
1. SOS: time for which the left edge has increased to 25% seasonal amplitude as measured from the left minima of the curve.	1. PV: maximum NDVI value for the fitted function during the season.
	2. BV: average between left and right minima curve. NDVI value during dormancy.
2. EOS: time for which the right edge has decreased to 25% seasonal amplitude from the right minima of the curve.	3. Amp: the difference between PV and BV.
	4. LI: integral of the fitted function describing the season and the zero level from the SOS to EOS.
3. LOS: time from the SOS to EOS.	5. SI: integral of the difference between the fitted function describing the season and the BV from the SOS to EOS. Vegetation production between dormancy and peak growth.

Table A2. NDVI time series data processing input setting in TIMESAT used for this study.

Parameter	Value	Description
Spike method	1	Spike method: 0 = no spike filtering, 1 = method based on median filtering, 2 = weights from STL, 3 = weights from STL multiplied with original weights.
Spike value	2	Determines the degree of removal and a low value will remove more spikes.
STL stiffness value	2	STL trend stiffness parameter. Its value is between 1 and 10 with a default of 3.
Seasonal parameter	1	A value close to 0 will attempt to fit two seasons per year and a value near 1 attempt to fit one season.
Number of envelope iterations	1	Number of iterations for upper envelope adaptation (3,2,1).
Adaptation strength	2	Envelope adaptation strength. The maximum strength is 10.
SG window size	4	The half window for SG filtering. Large values will give a high degree of smoothing.
Start/end of season	1	Season start method for determining the start/end of the season based on the intersection of the fitted curve: 1 = Seasonal amplitude, at the point where the curve intersects a proportion of the seasonal amplitude; 2 = absolute value, at the point where the curve intersects an absolute value in units of the data; 3 = relative amplitude, at the point where the curve intersects a proportion of a relative seasonal amplitude; 4 = STL trend, at the intersection with the trend line from STL.
Season start/end	0.25	Values for determining season start/end. If the start method is 1 or 3, the value must be between 0 and 1.

Table 8.2: Table A1.Correlation coefficients of seasons during the study period and seasonality parameter values.

9. Manuscript IV: Climate (im)mobilities in the Eastern Hindu Kush: The case of Lotkuh Valley, Pakistan

Outline

Bibliographic Information

Khan, S. A., Sass, O., & Doevenspeck, M. (2024): Climate (im)mobilities in the eastern Hindu Kush: The case of Lotkuh Valley, Lower Chitral in northern Pakistan. Population and Environment, 46:2. `https://doi.org/10.1007/s11111-023-00443-2`

Article Adaptation

The contents of the original version had to be slightly modified for its inclusion in this dissertation, including the numeration of sections, figures, tables, and equations had to be adjusted. The published version of this article can be found at `https://doi.org/10.1007/s11111-023-00443-2`.

Abstract

The relationship between climate, environment, and human mobility is complex as (im)mobility outcomes are influenced by multiple socioeconomic, political, and environmental factors. The current debate is focused on migration as an adaptation strategy in the face of climate change but largely ignores the immobility aspect, particularly in the Eastern Hindu Kush where mountain livelihoods are strongly dependent on local environmental conditions. In this study, we examine the interrelations between climate change and the environment as drivers of human mobility and immobility in the mountain communities of Lotkuh valley, Chitral in north Pakistan. We employed a mixed methods approach grounded in migration theory to describe the relationship between climate change, environment, and (im)mobility outcomes. The study reveals that climate (im)mobilities are the outcome of a complex interplay between climate change, extreme events, and local livelihoods. The primary drivers of (im)mobility are socioeconomic factors. Forced displacement is driven by a multitude of extreme events in the area. Three critical aspects of livelihoods – land resources, crop productivity, and livestock farming are identified as significant factors influencing mobility and immobility outcomes. Recurring extreme events such as floods and landslides exacerbate soil erosion and the loss of fertile farmlands, leading to food insecurity and compelling households to resort to labor migration as an adaptation strategy. Conversely, for households facing severe income stress and depleted economic assets, immobility becomes the only viable option due to insufficient resources for migration. Moreover, the study reveals that some households adopt a mixed strategy by sending select members to other areas while others remain in their places of origin to sustain their livelihoods. The study has implications for policymakers, government, and development organizations in the region suggesting sustainable livelihoods and adaptation measures to address the specific challenges faced by mountain communities in the Lotkuh Valley and the wider region.

9.1 Introduction

With the increase in research on climate change and its impacts, the academic and public policy discourse on the linkages between environment, climate, and human migration has also gathered momentum (Piguet, 2010, 2022; Wiegel et al., 2019). These linkages are intricate and multifaceted and (im)mobility decisions are influenced by a multitude of drivers (Boas et al., 2019; Boas et al., 2022; McLeman & Gemenne, 2018; Parsons & Nielsen, 2021). The purpose of this study is twofold: (i) to examine current mobility and immobility patterns and their drivers in the Eastern Hindu Kush, and (ii) to assess the influence of climate change on these patterns by analyzing its effects on mountain livelihoods. We provide empirical evidence to fill a knowledge gap in the field of climate change and human (im)mobilities in the Eastern Hindu Kush, and conceptualize our findings to contribute to the wider literature on climate (im)mobilities.

Our research builds on the two subsets of the climate change and (im)mobility nexus literature; firstly, the debate on climate change, environment, and (im)mobility, and secondly, the empirical evidence of climate change impacts on the livelihoods and their relationships with (im)mobility patterns in the mountain regions. To achieve this, we employ a mixed-method approach in this study. Theoretically, the study invokes a synthesis of the new economics of labor migration, the aspirations and capabilities framework, the livelihoods approach, and the foresight framework, to show the complexity of links between climate and human (im)mobility. The remainder of this paper is structured as follows: We begin with an overview of the environment, climate change, and (im)mobility nexus by including the mountain communities in this debate, followed by our theoretical positioning and a description of the study area. Next, we present our data collection and analytical methods, presenting results covering mobility patterns, drivers of mobility and mobility, mountain livelihoods and climate (im)mobility. We then discuss our findings in relation to existing climate migration literature in the discussion section. The paper concludes by highlighting our key contributions to climate mobilities literature.

9.2 Environment, climate change, and human (im)mobility nexus

The debate on climate change and migration nexus began with earlier studies that predicted mass migration of “climate refugees” due to the supposed failure of millions of people to adapt to the adverse impacts of climate change (Biermann & Boas, 2010; Myers, 2002). This “alarmist” view considered the mass exodus to have implications for security and stability globally, thus dominating the climate change-security agenda (Wiegel et al., 2019). The main criticism of this view is the assumption of the monocausal link between climate change and people’s movement (Black, Adger, et al., 2011; Doevenspeck, 2011; Wiegel et al., 2019). These estimates are based on a deterministic view and ignore socio-economic, political, and cultural drivers and human agency in migration decision-making (Black, Adger, et al., 2011; Gemenne, 2011; Romankiewicz & Doevenspeck, 2015).

The criticism of the alarmist perspective led to the rise of the ‘migration as and adaptation’ discourse in which the relationship between climate, environment, and migration is considered complex (Wiegel et al., 2019). Most scholars argue that migration is influenced by a multitude of factors including individual agency, adaptation capacity, and the broader sociocultural, economic, and political context (Black, Adger, et al., 2011; Boas et al., 2019; Romankiewicz et al., 2016). Migration is and has always been an important adaptation strategy to the changes in the socio-economic, political, and natural environment (Groth et al., 2020; Hunter & Simon, 2022; McLeman, 2018; Wiegel et al., 2019). Furthermore, migration is a multicausal phenomenon, and environmental factors are among many other drivers that impact migration decisions (Kaczan & Orgill-Meyer, 2020; Morales-Muñoz et al., 2020). The focus of empirical research has largely been on human mobility or migration, with limited attention given to immobility, i.e., on the people who stay despite facing adverse conditions, often termed as ‘trapped populations’ (Zickgraf, 2018, 2021b). However, immobilities in the face of climate change is the subject of an increasing number of studies (Ayeb-Karlsson, 2020; Khatun et al., 2022; Piggott-McKellar & McMichael, 2021; Schewel, 2020).

In the recent debate on the climate change and migration nexus, there has been a shift from climate or environmental migration toward 'climate mobilities' (Boas et al., 2019; Cundill et al., 2021). This perspective advocates for a broader understanding of the relationship between human movement and climate change which covers the diversity of movement rooted in the local historical, structural, and political context (Boas et al., 2022; Wiegel et al., 2019). Moreover, it entails that human movements in the context of climate change take shapes of different mobilities and immobilities such as short-distance forced displacement, long-distance migration, and rural-to-urban migration (Boas et al., 2022). In addition, it also involves the immobility of people when they cannot or do not want to move out of areas of climate risk. Therefore, the plurality of various mobilities cannot be captured by the term migration in the context of climate change (Boas et al., 2019). The climate mobilities perspective is molded in the broader 'mobilities paradigm' (Sheller & Urry, 2006) which involves analyzing how movement plays a fundamental role in social institutions and practices, and exploring various forms of mobility and their diverse combinations (Sheller & Urry, 2016).

Environmental changes can influence mobility directly by posing risks to the life and health of vulnerable people or through their interaction with socioeconomic and political drivers (Hoffmann et al., 2020). The direct link between a rapid-onset event (e.g., floods) and mobility could be if, for instance, the destruction of homes or their livelihoods, such as erosion of agricultural land, forces people to relocate or be displaced to another place. Such movement is generally for a short duration and over a short distance, and people return to rehabilitate their damaged houses and property (Cattaneo et al., 2019; McLeman & Gemenne, 2018). Indirect links are where slow-onset events (e.g., droughts, land degradation, changes in precipitation) impact local environmental and agroecological conditions, resulting in some people moving to other places because of the decline in agricultural productivity in the area (Anjum & Fraser, 2021;

Zickgraf, 2021a). Slow-onset changes and extreme natural events interact with contextual factors (e.g., income, land tenure, and gender) and affect a household's vulnerability and capability differently (Kaczan & Orgill-Meyer, 2020). Generally, rapid-onset events or extreme events deplete the household's asset base and undermine their ability to migrate, while the slow-onset requires people to adjust to these changes by choosing out-migration (Cattaneo et al., 2019; Kaczan & Orgill-Meyer, 2020). However, this decision-making is dependent on the macro-level socioeconomic and political conditions of the area (Hoffmann et al., 2020).

Overall, the relationship between climate change and migration is stronger in areas where people's livelihoods are dependent on the environment (Piguet, 2022). In such regions, people's livelihoods are threatened by the impacts of natural hazards (both rapid-onset and slow-onset events) and exacerbate the pre-existing socio-economic vulnerabilities, which in turn affect their migration decisions (Cundill et al., 2021). However, the poorest communities who lack the resources to undertake migration may not be able to move and thus could become 'trapped' populations (Black, Bennett, et al., 2011; DeWaard et al., 2022). Apart from this involuntary immobility, some households voluntarily prefer to stay in their places of origin and lack migration aspirations (Rabbani et al., 2022; Zickgraf, 2018).

Climate change has significant implications for mountain communities, including those in the Hindu Kush, Karakoram, and Himalaya (HKH) region, with the reduction in glacier cover, changes in water supply, increased hydro-meteorological hazards, and changes in land cover (Khan et al., 2022; Kulkarni et al., 2013; Sabin et al., 2020; Wester et al., 2019). These climatic and environmental changes affect livelihoods, which are heavily dependent on the local environment, limited agriculture, fragile and scarce resource base, and structural dependence on lowland areas (McDowell et al., 2019; Siddiqui et al., 2019). Migration plays a significant role in the diversification of the livelihoods of mountain communities in addition to providing better education and better life opportunities (Gioli et al., 2016; Siddiqui et al., 2019). However, remittances from migration are prioritized for household consumption, education, and healthcare needs over investment in agriculture or adaptation measures in the HKH region (Siddiqui et al., 2019). The frequent natural hazards such as torrential rains, floods, avalanches, and landslides coupled with socioeconomic, political, and demographic changes have outcomes for their mobility and immobility. Studies on climate, environment, and migration have been conducted in parts of HKH (Benz, 2016; Childs et al., 2014; Gioli, Khan, Bisht, & Scheffran, 2014), with little focus on the immobility aspect. There is a general lack of knowledge on the climate mobilities in the mountain communities of the Eastern Hindu Kush region. Moreover, climate immobility is an understudied aspect in the growing global environment and migration literature (Blondin, 2021; Cundill et al., 2021).

Considering a recent review of migration theory in climate mobility research, which argues that empirical literature on climate migration has grown in isolation from the advances in migration theory (Sherbinin et al., 2022), our approach is shaped the synthesis of several theoretical approacheds since a single one cannot fully capture the non-linear relationship between environment, climate change and human mobility: push-pull, NELM, aspirations and capability framework, livelihoods approach, and Foresight framework. Accordingly, we define migration aspirations as people's ambitions and preferences about life in their villages and their perceptions of opportunities in destinations (De Haas, 2021). Migration capabilities are the social and economic resources needed for people to move dependent on positive and negative liberties (De Haas, 2021). Negative liberty denotes the presence of external constraints, obstacles, or barriers that are often enforced by the macro context, such as government policies, and positive liberty means "the ability to take control of one's life and to realize one's fundamental purposes" (De Haas, 2021, p. 24).

We also acknowledge that even those without migration aspirations but exposed to significant risk and in dire situations may still not be able to move (Boas et al., 2019; Suckall et al., 2017). There could also be involuntary immobility of individuals due to a gap between aspiration (to move) and capability to do so (De Haas, 2021). In other cases, they are forcibly displaced by drivers such as floods. The forced displacement is generally a short-term and sudden involuntary movement of households and communities from their place of residence often triggered by extreme events (Adger et al., 2018). We understand migration capability (De Haas, 2021) as the social, cultural, and economic resources that enable a person to realize their move to a new place. Natural hazards and extreme events act as push factors affecting income, land, and other economic assets while better employment opportunities, family networks, and income at the destinations serve as pull factors. We regard climate change as an indirect driver of migration where it interacts with economic conditions leading to migration as an adaptive strategy by households or immobility for others, thus conforming with Foresight and livelihoods frameworks (Black, Adger, et al., 2011; Scoones, 1998). We also consider human mobility and immobility to be interconnected and should be studied together as noted in the climate mobilities perspective (Boas et al., 2022; Wiegel et al., 2019). We placed the decision-making process of (im)mobility within the household context (as informed by NELM and livelihoods approach), considering it a collective decision influenced by the household head but also taking into account individual and household aspirations. To operationalize this, we employ the concepts of (including natural resources, financial resources, education, skills, and social networks) and livelihoods (skills, resources, and activities) from the sustainable livelihoods framework (Scoones, 1998). The livelihoods framework is criticized for its lack of attention to cultural and power relations within the households (Adato & Meinzen-Dick, 2002). While acknowledging these limitations, we use the livelihoods approach to explore the livelihoods and capitals of the households and the relationship between these assets and climate change and extreme events in our study area.

To investigate the relationships between environment, climate change, and human (im)mobility patterns, we focus on the Eastern Hindu Kush, especially the Lotkuh Valley, in north Pakistan. Currently, it is ranked as the 8th most affected country over the last twenty years (Eckstein et al., 2021), and among the high-risk countries globally for humanitarian crises and natural disasters (Thow et al., 2022). Remote mountain communities in northern Pakistan are experiencing rapid socio-economic, environmental, and demographic changes (Wester et al., 2019), heavily depend on agriculture for their food security and livelihoods, and face the depletion of natural resources, lack of access to the market, poor infrastructure, and a small local economy (Rasul et al., 2019). The agriculture in mountain areas of northern Pakistan is fed by irrigation networks spanning long distances dependent on glacial meltwater and snow cover (Nüsser, 2001; Nüsser et al., 2019; Parveen et al., 2015). The agriculture-based livelihoods are susceptible to the impacts of climate change (Ajani & van der Geest, 2021). Fast-onset events such as glacial outburst floods, erratic rains, snow avalanches, and landslides disrupt the irrigation networks, erode agricultural land, damage the public infrastructure, and pose risks to the livestock, human settlements, and the local environment (Elalem & Pal, 2015; Khan et al., 2022; Nizami et al., 2019; Nüsser, 2001; Vaidya et al., 2019). The changes in precipitation and temperature result in water scarcity, affect crop growth, and result in low agricultural productivity (Ahmad et al., 2020; Ajani & van der Geest, 2021; Nizami & Ali, 2017).

Our study area – Lotkuh Valley is located in the Eastern Hindu Kush and is administratively part of the Lower Chitral district of Khyber Pakhtunkhwa province in Pakistan (Figure 9.1). The semi-arid study area with the three sub-valleys Arkari, Garum Chashma, and Karimabad has a complex topography and is exposed to multi-hazards. Migration from the remote villages of northern Pakistan, including Chitral, to the other cities, is not a new phenomenon (Rahman, 2007). However, it increasingly serves as an adaptation strategy to adjust to the decreasing agricultural productivity in the face of environmental changes and respond to extreme events (Gioli, Khan, Bisht, & Scheffran, 2014; Gioli, Khan, & Scheffran, 2014). Previous research in the Eastern Hindu Kush included migration patterns in Lower Chitral and Upper Chitral (Holdschlag, 2000), seasonal migration of herders (Nüsser & Holdschlag, 2012), and male out-migration from Melph valley (Rahman, 2007). However, scholarship on climate–environment–migration relationship in mountain communities in northern Pakistan is very limited. Climate (im)mobilities, particularly in Chitral and the Eastern Hindu Kush region, are largely not investigated.

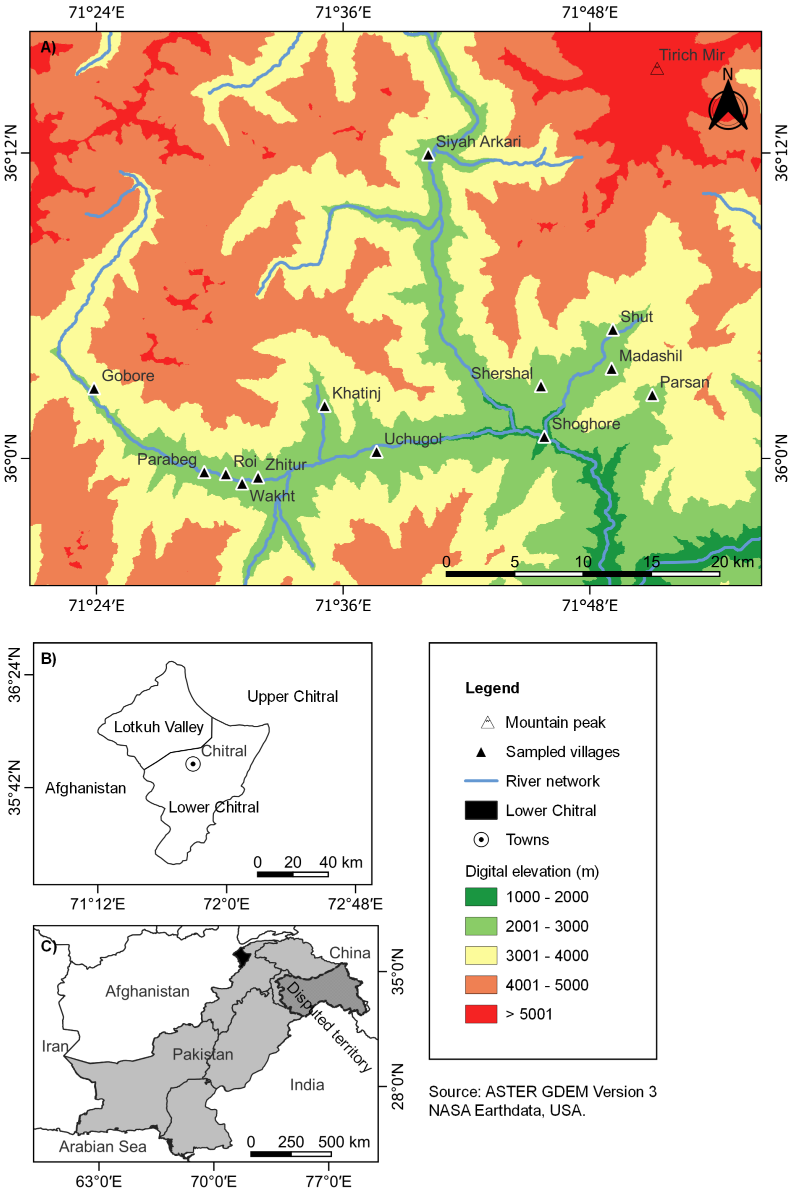
9.3 Methods

In this study, a mixed method approach (Bazeley, 2017; Creswell & Clark, 2017) comprising quantitative and qualitative techniques was used to collect data from 13 villages in the Lotkuh valley (Table 1). Informed consent from all the participants in this research was received before collecting any data. Both the data collection and analytic methods are explained below.

9.3.1 Data collection

For our study, villages were selected using a purposeful sampling method guided by a set of carefully considered criteria. These criteria, which were deliberated upon with the local research teams and contacts in Lotkuh Valley, encompassed various aspects, including the geographical setting, agroecological conditions, susceptibility to natural hazards, patterns of out-migration, logistical feasibility, and cost considerations. As a result, a total of 13 villages were selected, representing the diversity present in the Lotkuh Valley. These selected villages, shown in Figure 9.1, represent a wide spectrum of characteristics, including varying altitudes, accessibility, community sizes, agroecological conditions encompassing both crops and livestock, exposure to diverse natural hazards, and divergent out-migration patterns.

The first part of our data collection methodology comprised a survey questionnaire that was administered to 388 households in sampled villages with the assistance of a locally trained research team. The sample size was calculated based on the population (approximately 45,000 inhabitants spread over 6,600 households) recorded in the national census in 2017. The sample size was distributed proportionally to the population and



Source: ASTER GDEM Version 3
NASA Earthdata, USA.

Figure 9.1: Map of the study area: A) sampled villages in the Lotkuh valley; B) the location of Lotkuh valley in the Lower Chitral district, and C) Lower Chitral in the northwest of Pakistan.

Villages	Population (2017 census)	Households (2017 census)	Households surveyed	Interviews conducted	Focus groups conducted	Natural hazards
Gobore	1028	114	26	2	1	Snow avalanche
Khatinj	206	30	11	2		Landslide
Madashil	735	108	33	4		Landslide, rockfall
Parabeg	1567	217	49	3		River erosion
Parsan	716	93	29	3		Rockfall, landslide, land subsidence
Roi	812	99	23	4	1	Debris flow
Shershal	485	78	24	2	1	Snow avalanche
Shoghore	491	69	26	3	1	River erosion
Shut	481	82	27	2		Landslide
Siyah Arkari	691	121	45	5	1	Debris flow, glacial outburst
Uchugol	987	146	56	3	1	Snow avalanche, rockfall
Wakht	410	58	14	4		Snow avalanche
Zhitur	786	109	25	4	1	Debris flow

Source: Population census (Government of Pakistan), fieldwork in 2020

Table 9.1: Summary statistics on the population, the number of total households, surveyed households, interviews and focus groups, and natural hazards in each village.

household units of the villages based on the latest census conducted by the government in 2017 (Table 9.1). Since the list of households did not exist for the villages, the households in each village were selected using the sampling interval starting from the one end of village and covering all the hamlets (locally called mohalla) within the village. Households were revisited in case the respondent was not available on the first visit. Overall, all the sampled households participated in the survey. It is worth noting that due to the purposive selection of the villages, the results from the sample may not be statistically generalizable to the region.

9.3.2 Data analysis

Summary statistics on respondents of this survey are provided in Table 9.2. The survey collected data on migration and immobility, including their drivers. Specific data was also collected on the migrants and involuntarily immobile persons (i.e. who have migration aspirations but lack the capabilities) including their gender, age, education, occupation, destination, and reasons for migration or immobility. Migration aspirations (education, healthcare, income opportunities, etc.) and capabilities (such as educational qualifications, economic resources to bear migration costs, and social networks) were covered together with other impacts of climate change and extreme events on their livelihoods.

To find out the relationship between mobility (migration and forced displacement), involuntary immobility, and climate change, we collected data on climate change and extreme events' impacts on livelihoods. Semi-structured interviews were carried out to explore the extreme events, their impacts, and coping strategies. Information was also collected on the perceived changes in precipitation and temperature and their effects on livelihoods. In interviews, we also gathered data on migration and immobility of household members including their drivers. The purposive sampling technique was used for the interviews. Forty-one interviews were conducted with individuals who are migrants or have migration experience in the past, immobile or belong to a household with migrants or immobile persons, and engage in agriculture or livestock farming. Finally, to provide broader socio-economic information on the area and to situate the data from the interviews and household survey, seven focus groups were organized in selected villages representing the overall diversity of the study area (Table **??**)). Data on livelihoods including agricultural practices, community experience of past natural extreme events, impacts of environmental change on agriculture, and (im)mobility and their drivers were collected. Participants in the focus groups included farmers, migrants, village elders, social workers, and persons representing different castes and hamlets within the village and their diverse experiences. Focus groups were organized in places usually where community meetings are events are held. Open-ended questions and prompts were prepared that guided the discussion.

Our data analysis approach consisted of a separate analysis of quantitative and qualitative data. The household survey was analyzed using descriptive statistics calculated for each relevant variable. These statistics allowed us to summarize and present key features of the dataset, providing a clear overview of our findings. Survey data was analyzed using R and SPSS. To further explain and enrich our quantitative findings, we analyzed our qualitative data gathered using interviews and focus groups. Based on transcription guidelines, the interviews and focus groups were transcribed in the Urdu language, then checked and translated into English by the lead author. The translated transcripts were then analyzed using the Qualitative Content Analysis (QCA) approach described in Kuckartz (2019). This involved preparing data for analysis, formation of main categories based on research questions, and then coding qualitative data with the main categories. Subcategories were formed inductively on the passages compiled with main categories. Finally, category-based analyses were carried out to formulate key results. QCA was implemented in the computer-assisted qualitative data analysis environment of the MaxQDA software (Kuckartz & Rädiker, 2019). Qualitative results from interviews and focus groups were interpreted and synthesized using the identified themes and sub-themes and using excerpts from the transcripts to illustrate key results. Moreover, findings from different focus groups and interviews were triangulated to increase the reliability and validity of the results. Finally, a complementary analysis of the various data sources involved analytic strategies such as producing a coherent picture using multi data sources, comparing and contrasting different data to enrich interpretation, and merging sources to create a detailed description (Bazeley, 2017).

9.4 Results

9.4.1 Mobility characteristics

Descriptive statistics of the household survey are provided in Table 9.2). Out of 388 surveyed households, 78% (n=301) reported migration compared to 52% (n=202) involuntary immobility of at least one or more

	Respondent	Migrants	Immobile persons
Households	388	301 (78%)	202 (52%)
Total count	388	561	273
Number of migrants/ immobile per household			
Mean	-	1.86	1.35
Median		1.00	1.00
Mode		1	1
Std. Deviation		1.232	0.607
Age			
N Valid	376	561	264
Missing	12	0	9
Mean	40.82	29.42	28.84
Median	38.50	27.00	26.00
Mode	35	25	25
Std. Deviation	15.363	11.023	10.954
Gender			
Female	97 (25%)	111 (19.8%)	62 (22.7%)
Male	291 (75%)	450 (80.2%)	211 (77.3%)
Education			
Illiterate	145 (37.4%)	77 (13.7%)	53 (19.4%)
Primary	44 (11.3%)	72 (12.8%)	38 (13.9%)
Secondary	85 (21.9%)	177 (31.6%)	86 (31.5%)
Islamic education	1 (0.3%)	2 (0.4%)	-
Technical	5 (1.3%)	27 (4.8%)	1 (0.4%)
College/university	108 (27.8%)	206 (36.7%)	95 (34.8%)
Occupation			
Agriculture	10 (2.6%)	3 (0.5%)	5 (1.8%)
Government employee	26 (6.7%)	55 (9.8%)	12 (4.4%)
Housekeeping	67 (17.3%)	20 (3.6%)	37 (13.6%)
Labor	65 (16.8%)	173 (30.8%)	62 (22.7%)
Others	4 (1.0%)	5 (0.9%)	1 (0.4%)
Private employee	28 (7.2%)	63 (11.2%)	13 (4.8%)
Retired	6 (1.5%)	2 (0.4%)	-
Self-employed	33 (8.5%)	26 (4.6%)	18 (6.6%)
Student	42 (10.8%)	133 (23.7%)	75 (27.5%)
Unemployed	107 (27.6%)	81 (14.4%)	50 (18.3%)
Migration status			
Migrant	47 (12.1%)	-	-
Non-migrant	341 (87.9%)		
Respondent as head of household			
No	167 (43%)	-	-
Yes	221 (57%)		
Migration destination			
Another village in Chitral	-	24 (4.3%)	13 (4.8%)
Chitral city		55 (9.8%)	37 (13.6%)
Other districts		446 (79.5%)	150 (54.9%)
Other countries		36 (6.4%)	73 (26.7%)

Table 9.2: Descriptive statistics of the survey. This table provides information on the total surveyed households and the corresponding number of migrants and involuntarily immobile persons. It also summarizes the individual characteristics including age, gender, education, occupations, and migration destinations. Immobile persons are those individuals who want to migrate but could not realize it due to socioeconomic, political, or environmental reasons.

members between 2010 and 2020. A total of 561 migrants and 273 immobile persons were reported by surveyed households. The gender composition of the migrants is 20% female and 80% male and of immobile persons 23% female and 77% male.

Both male and female migrants are found in all villages except Shershal which has 100% male migrants. About 37% of migrants are college/university graduates (35% for similar education for immobile persons), 32% have secondary education (a similar number for immobile persons) and 14% are illiterate (19% of immobile persons). Among 5% of migrants have technical or professional education in contrast to only 0.5% of immobile persons with such qualifications. The top occupation for migrants is labor work (31%) in contrast to immobile persons who are currently receiving education (27%). Migrants' destinations are other districts (80%) in the country or a foreign country (6%) in contrast to immobile persons' intended destinations are other districts (55%) followed by a foreign country (27%).

Migration trend in Lotkuh valley is from rural to urban areas. Labor migration is primarily undertaken to regional trade hubs such as Chitral town and Gilgit, as well as major cities, particularly Peshawar, Rawalpindi, Lahore, and Karachi. On the other hand, education-related migration is more concentrated in cities such as Peshawar, Islamabad, Rawalpindi, Lahore, and Karachi. While international destinations for migrants are predominantly Gulf countries. Temporally, migration in the Lotkuh valley can be classified into three categories: seasonal, temporary, and permanent. The most common type of migration is temporary, which is reported by 75% of migration households. Temporary migration involves people's movement to urban centers for a limited period to pursue education and employment opportunities, to eventually return to their villages. In addition to temporary migration, about 13% of migration households engage in seasonal labor migration, which takes place in the winter. Finally, 12% of migration households reported permanent migration of their members who settled permanently in urban centers.

Our findings suggest that there are similar age, gender, and educational level distributions between mobility and immobility groups. However, the importance of the destination differs significantly between the two groups. Specifically, a higher proportion of the immobility group intends to migrate internationally (27%) compared to the migrant group (6%). In contrast, a higher proportion of the migrant group moved to other districts or cities (80%) compared to the immobility group who wanted to move to other districts (55%). Qualitative data shows that aspirations to migrate internationally are not met due to lack of financial resources and networks and then alternatively migrants choose internal migration. The increased migration of young women in Lotkuh valley is a relatively new phenomenon, primarily driven by educational aspirations, particularly in nursing education. Many of these women are later employed in hospitals in cities such as Karachi and Peshawar.

Another form of mobility in the Lotkuh valley is the displacement caused by extreme natural events. A total of 83% of households (n=321) were affected by an extreme event during 2010-2020. During this period, 45% of surveyed households reported displacement due to an extreme event. The drivers of displacement, migration, and immobility are described in the next section.

9.4.2 Multiple drivers of migration, immobility, and displacement

The survey results (Figure 9.2) show that there are multiple drivers of migration in the Lotkuh Valley. Socioeconomic drivers are predominant. Access to better education (40%) and health facilities (75%) are considered important factors in migration decision-making by households. The younger migrants move to Chitral town, Peshawar, Karachi, and other cities to receive college and university education. Similarly, access to better health facilities in these cities is also perceived as an important factor in migration decision-making. Health services are inaccessible particularly in the winter seasons due to snowfall and avalanches. Migrants sometimes relocate vulnerable family members to other locations for the winter seasons. The presence of migrants' social networks and family connections (23%) in destinations also contributes to migration and the choice of these destinations. Political drivers such as conflict within the community (1%) and lack of political freedom (1%) are rare in the Lotkuh Valley, we believe this rarity may be attributed, in part, to the absence of significant religious and ethnic tensions in the valley presently. However, focus group data revealed that such tensions existed before the merger of the Chitral state into Pakistan. Moreover, we identified the development of key infrastructure, specifically the Lowari pass and tunnel, as playing a role in increasing mobility to the lowlands. Furthermore, factors such as the visa process, availability of information, and social networks in other countries were highlighted as elements that can either drive mobility or their absence can contribute to immobility. The survey results revealed that discrimination did not play any role in (im)mobility decisions. Focus groups highlighted that destinations with the presence of religious communities (of Ismaili) are preferred for migrants to other places. However, these findings require further exploration to develop a nuanced understanding of the underlying dynamics at play. It is also obvious from Figure 2 that economic motives weigh heavily on migration decision-making. Migrants reported employment opportunities (74%) and higher income (59%) at the destinations as the main economic reasons for migration. Similarly, about 45% of migrants also cited unemployment at their place of origin. Moreover, one-fifth of migrants cited lack of agricultural land (22%) and crop failures (20%) as the motives while not enough income (29%) at the place of origin also contributed to their migration. To consider the interrelationships between climate change, environment, and human migration, we also asked about various natural hazards and changes in climatic conditions. Heavy snowfall and rainfall (36%) related extreme events contributed significantly followed by landslides (21%), floods (9%), and cyclones and storms (2%). Water shortages and drought-like conditions were mentioned by a mere number of migrants (1%). Migration decision-making takes place at the household level and is often influenced by the head of household who is mostly a male member. Factors such

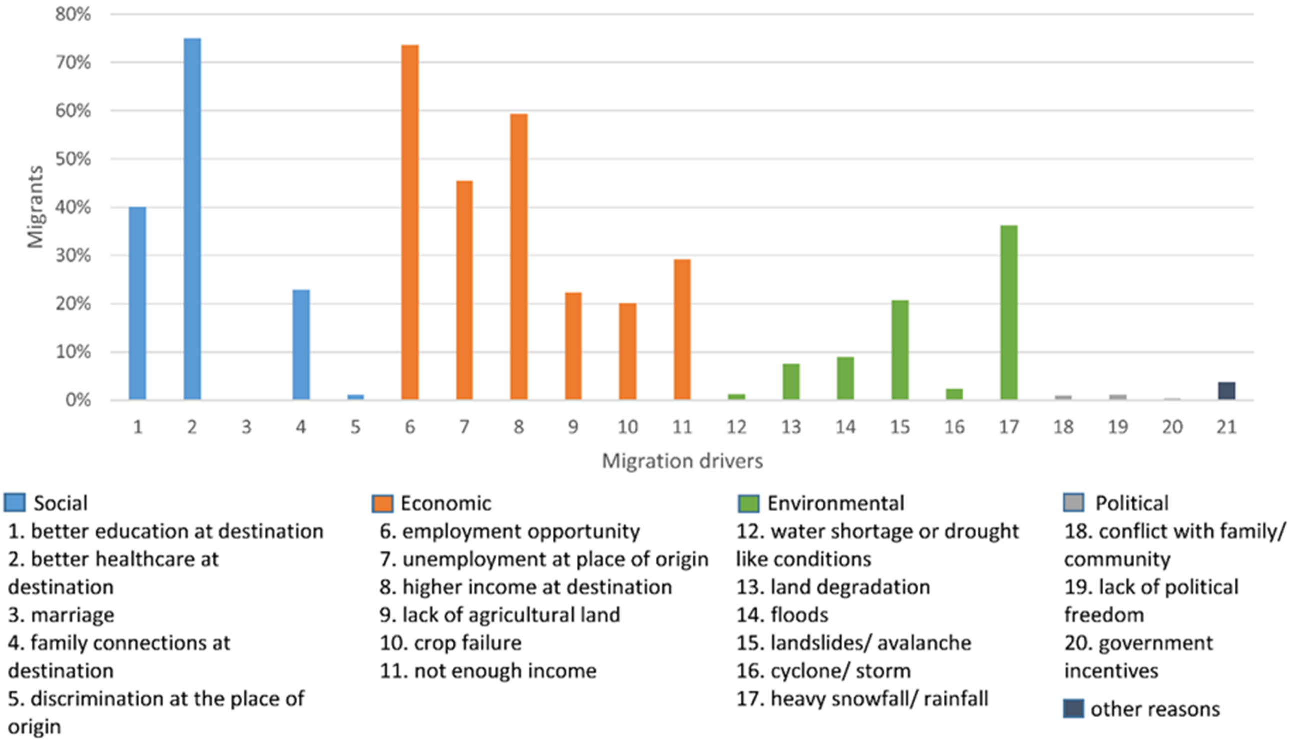


Figure 9.2: Drivers of migration in the Lotkuh valley

as education, migration costs, social networks in places of destinations perceived likelihood of job, and income influence migration decisions.

About 52% of surveyed households (n=202) reported immobility of 273 members (211 males, 62 females). Figure 9.3 shows various factors of immobility for these persons. Overall economic barriers to migration are quite prominent such as a lack of financial resources (73%) that are used to meet basic household needs. Other environment-related drivers include the impact of extreme events on income (36%), loss of their economic assets (24%), the collapse of transportation networks (11%), and more manpower required for land rehabilitation (25%). Noticeable social reasons include lack of education (39%), health reasons (30%), and responsibility to take care of household work (59%). In terms of displacement, it is triggered by several extreme events in the Lotkuh valley. Out of surveyed households (n=388), floods (28%), earthquakes (23%), and avalanches (16%) are the main drivers of displacement (Figure 9.4). In addition, erratic rainfalls (11%), snowfall (6%), and landslides (56%) also

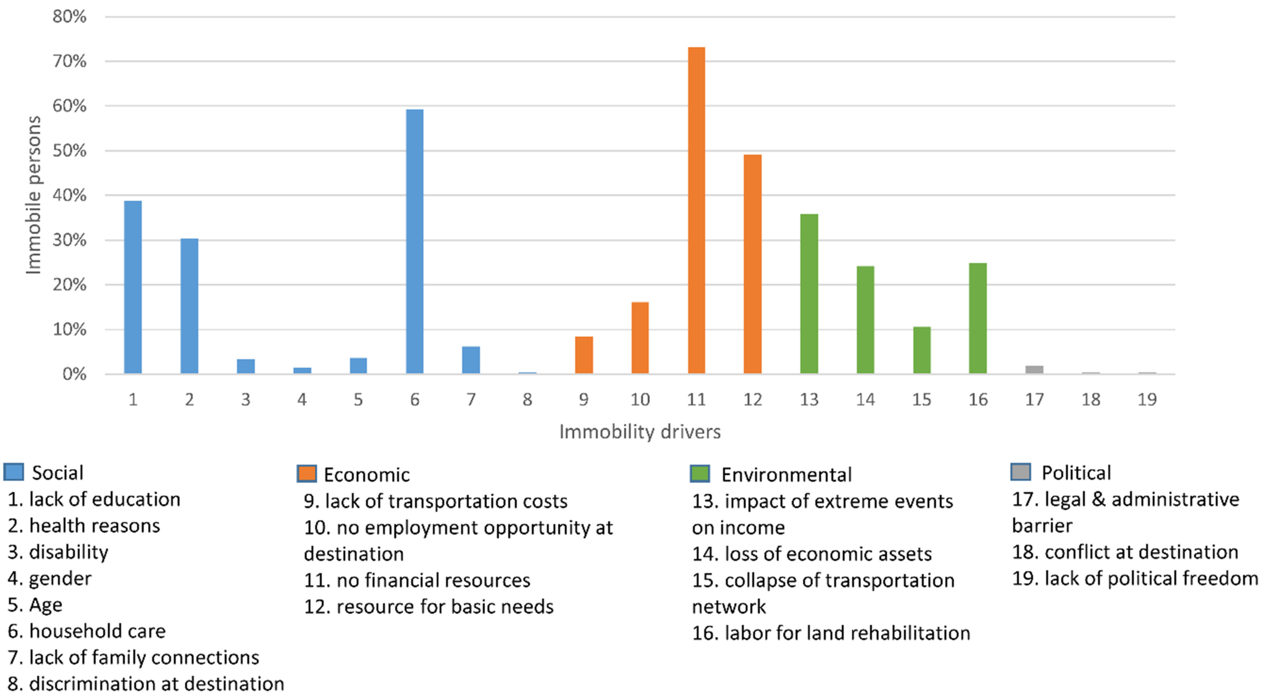


Figure 9.3: Drivers of migration in the Lotkuh valley

caused the displacement of households. The displacements were forced by a multitude of factors such as the severity of the potential risk and the likelihood of loss of human life, and precious assets such as houses and livestock. It is undertaken mostly in the aftermath of an event or some cases before the event if a warning is received. This escape mobility is short-term, from a couple of days to a couple of weeks, and is over a short distance (such as a safe place in the village or nearby areas). Communities organize the assistance of food rations and shelter, sometimes with the support of local organizations and the government to provide to the displaced families during this displacement period. In the following section, we explore how extreme natural events and climatic changes affect their livelihoods leading to their migration or immobility outcomes.

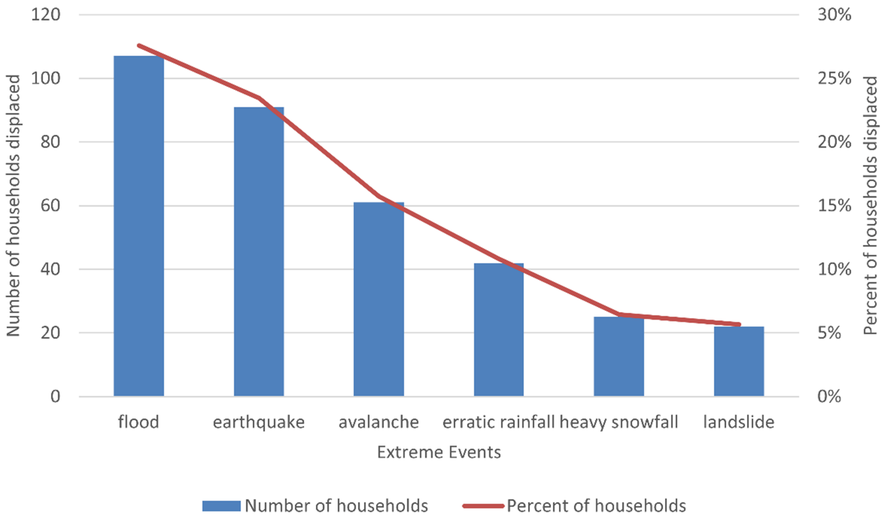


Figure 9.4: Drivers of involuntary immobility in the Lotkuh valley

9.4.3 Mountain livelihoods and climate (im)mobility

The livelihoods in the mountain communities of Lotkuh valley are based on subsistence agriculture and livestock farming coupled with income from labor migration. People consider land as an important resource that is susceptible to the impacts of climate change and associated extreme events. In the following, we explore the climate (im)mobilities in the local livelihoods context through the interaction of climate change and extreme events with land degradation, crop productivity, and livestock farming.

Land degradation

Natural hazards and associated extreme events, especially floods, landslides, rockfall, and snow avalanches cause erosion and degradation of the scarce land in mountain communities of Lotkuh valley. According to our survey, the foremost impact of these natural events is soil erosion in which land, both urban and farmland, is eroded by floods (45%), landslides (18%), and avalanches (18%). Similarly, these hazards (floods: 12%, landslides: 7%, and avalanches: 6%) mostly triggered by heavy precipitation are devastating as they bring debris and sediments given the topography of the area and cause land degradation in the floodplains. The situation in Arkari village which is frequently affected by floods is described below:

> *"A lot [of agricultural land] from the lower side [of stream which connects it the river]. My own large agricultural field was washed away by this flood in this stream. The floods from Dhirgol [a local tributary of Arkari river], there were 3 or 4 large floods. The large flood was in 1977, then in 2010 and then a very dangerous flood came in 2015."* (Interview, Siyah Arkari village, August 2020)

As in the case of Arkari and similar to other villages, farmland lies mostly along the riverbanks and the recurring floodwater erodes them and causes them to collapse resulting in loss of land for the farmers. Flooding also erodes the fertile topsoil damaging the growth of crops and plants in the future. In addition, flash floods, avalanches, and landslides also bring down sediments such as sand, rocks, and boulders to the farmlands which degrade the farmlands. In some cases, farmers spend a lot of financial resources to rehabilitate the affected lands while some of these huge boulders cannot be removed from the lands. Moreover, farmers said that many such affected lands cannot be restored and are not cultivable anymore. This leads to the abandonment of land by some households.

A prime example of land degradation is the village of Shoghore, where it is a regular phenomenon for the farmers, due to its physical location at the confluence of three tributaries of the Lotkuh river. It is frequently affected by floods, sometimes simultaneously by more than one tributary in extreme flooding years of 2010, 2015, and 2016, as narrated below:

> *"That one [river], which comes from Karimabad, causes erosion and destroys lands from the one side, and the other one which comes from another side brings sand and gravel. The lands are being degraded because of this."* (Interview, Shoghore village, August 2020)

Another example is Parsan village in Karimabad valley which is experiencing the problem of landslips or land subsidence. The agricultural land is being lost or degraded as a result of the landslips. Moreover, farmers in Parsan face a lot of difficulty in irrigating their crops as the water seeps into the land and cannot reach the crop fields. The land subsidence is destabilizing the whole area and affecting the houses which require regular repair and maintenance, thus migration becoming a more suitable strategy for them. When a migrant was asked about his migration and its connection with the ongoing land subsidence in Parsan, he said:

> *"Yes, it has a link with the landslides because you cannot construct a concrete house in the village, cannot invest. House will survive for 5 years or a maximum of 10 years. Because of this [people] build ordinary houses. [We] go to grow crops in our fields, stay for two to four months. That's why we do not stay there and those who stay there have to rebuild their houses."*(Interview, Parsan village, July 2020)

The above results show that soil erosion and land degradation are important factors in local livelihoods context, and strain on the income as well food security of the households. To offset the losses incurred by land degradation, households engage mostly in a mixed strategy where some members undertake migration to urban centers and some stay in their villages to cultivate their agricultural lands. Those who remain in their villages are responsible for managing social relations as well as agricultural lands. There are also people who *"lend their lands to others for farming"* if they do not find it viable and move to other places for labor migration.

It was also mentioned that the availability of financial resources to cover the costs of migration is an important factor when considering mobility decisions. The extreme events amplify the lack of financial capacity of the household resulting in the immobility of its members as they do not have enough financial means for migration to their desired local (e.g., Karachi) and international destinations (e.g., Saudi Arabia). For some, the attachment to their land also plays a role in their immobility, and for others *“living here [in their villages] is also a compulsion”*.

Crop production

People engage in subsistence agriculture in the Lotkuh valley by growing various staple crops (such as wheat, and maize) and cash crops (potatoes, tomatoes, peas, etc.). Natural extreme events reduce the agricultural yield through their adverse impacts on standing crops, irrigation and other rural infrastructure. Floods (22%), heavy rainfalls (7%), and landslides (3%) which occur mostly in the spring and summer seasons, destroy the standing crops. The crops are prone to these extreme events, particularly the wheat crop which serves as the main crop for household food security. Crash crops such as potatoes if affected by floods cause a lot of financial strain for the households as they are more labor and cost-intensive. Farmers’ selected accounts of crops being affected by these natural events are given below:

> *”The first flood which I remember occurred in 1977. It was a massive flood because of rain, in the Shah Galogh. This flood was caused by rain and it uprooted, we plant trees along the banks, all of them and took away. People [lives] were not affected and were safe during the flood. [It] washed away so many trees and plants. Then in 2010, again a flood occurred driven by rain ... The one [flood] which came in 2010, was massive and it washed plants and trees away. [The damage] was mainly along the riverbanks and mainly trees. Then after this, a very dangerous flood came in 2015. On the one side of my house, the trees which are not fruit trees which I planted myself, 7000 to 8000 plants. They were quite grown, all were uprooted and taken away [with the flood].”* (Interview, Siyah Arkari village, August 2020)

Irrigation channels in the Lotkuh valley often span long distances. They are constructed from the upper part of the valleys to the cultivated areas and are very prone to disruption by landslides, avalanches, and floods (Nüsser, 2001). Similarly, floods (30%), landslides (12%), and avalanches (10%) cause damage to the irrigation infrastructure which includes both main irrigation channels from the water source and then water courses in the fields. The damage to the irrigation network affects the supply of irrigation water for crop cultivation and raising. The affected channels are regularly, and sometimes urgently, repaired requiring a lot of communal effort and costs. In some places that face these extreme events frequently, farmers require restoration of the irrigation network annually, as stated below:

> *”Water channels that are constructed [for irrigation] are disrupted by avalanches and floods. We rehabilitate them [water channels] every year.”* (Interview, Gobore village, July 2020)

Aside from the extreme events, climate change-induced changes in precipitation and temperature also negatively affect crop production in the area. The survey results suggest that 96% (n=372) and 92% (n=356) respondents perceive that temperature and precipitation have changed over the last 20 years respectively. The hot summer season causes the crops to ripe earlier and often with less yield. Fruit crops are more vulnerable to heat stress. The harvesting period has also shifted from August to July with a difference from 10 to 20 days in different places. Moreover, erratic rainfalls, such as monsoon (47%) which is more intense, at the time of harvest combined with warmer summer (63%) result in either destruction of standing crops, or a reduction in yield due to diseases. The snowfall in the previous year also influences the availability of water for the next crop season. Generally, participants felt snowfall (62%) is decreasing and glaciers as a result are on the decline. Selected perceptions on the impacts of climate change on crop production are in the following:

> *”When the summers are warmer, the harvest of the crop is reduced. When the summer is intense and rainfall [occurs] then the crops are infected with a disease, then this causes*

> *crop loss. This year the crops have turned bad."* (Interview, Siyah Arkari village, August 2020)

Few farmers contradict this, particularly those living in colder places, who attribute the rise in summer temperature to more production of fruits and crops in cold places, as described below:

> *"It is hotter now [in summer]. Temperature is on the rise. In former times, there was a place on the upper side [at a higher elevation] where there were no crops and fruits grown. But now there are good crops and good fruits are grown which tells us that summers are becoming warmer."* (Interview, Siyah Arkari village, August 2020)

When he is asked about the effect of warmer summers on agricultural yield, he responds *"It does not affect much"* instead *"agriculture yields more in warmer summers"*.

The interviews and focus group data showed that the failure of a wheat crop or a reduced yield leads to economic stress for the households for the whole year requiring them to procure wheat grain and flour from the market. Moreover, the households that face the failure of crash crops are severely stressed as they incur the loss of investment and potential. Some people find crop cultivation simply not worth the effort and rather *"prefer employment and labor wages instead of plowing"*. People also highlighted that forest depletion, caused by their over-exploitation for livestock and fuel wood, also stresses households' economic burden as they have to purchase fuel wood. Many households find the income from subsistence agriculture marred by the impacts of extreme events and changes in temperature and precipitation simply not enough to meet their expenditures. To cope with a deficit in on-farm income, households seek labor migration, either seasonal or temporary, as an adaptation strategy as voiced by the following interviewees:

> *"I do farming. I am also a tailor. Apart from this, I also go to the city [for labor migration]. I go there thinking about how*

> *much money to give to my family and where to spend it. The income from the farmlands is not enough for the family. We have to purchase everything."* (Interview, Roi village, August 2020)

Moreover, it was also observed that some households associated the effects of extreme events on crop productivity and labor migration more strongly than changes in precipitation and temperature. This is due to higher costs and effort required for land rehabilitation thus leading to more seasonal labor migration to generate revenue. There are also a few instances in which houses were relocated to other places due to frequent extreme events, but this could be due to the availability of land in relocation places.

The economic stress or lack of finances caused by extreme events and climate change are also perceived by households as a barrier to their mobility or a cause of immobility. For instance, the interviewee responds *"How can we poor people migrate?"* when asked about migration. Without sufficient money, the households cannot afford the costs associated with migration, as stated below:

> *"If they do not have money, they cannot afford the cost of migration. So that's why they cannot migrate. There are such reasons that people want to migrate but cannot."* (Interview, Shershal village, June 2020)

In such cases, immobility is caused when economic assets and income are eroded by extreme events and climatic changes resulting in a lack of capabilities to migrate.

It was noted from the interviews and focus groups that the households prefer a mixed strategy where some members of the family engage in out-migration while others engage in agriculture including those who are immobile. This strategy enables them to generate food from agriculture, and income from labor migration which is used to build household assets and also meet other needs, and those who stay in the village also fulfill their social obligations there.

Livestock farming

Interviews and focus groups show that livestock farming has been declining in the Lotkuh valley in the recent past. When asked about the reasons for this decline, local people associate this with several factors. Out of 81% of households (n=321) affected by an extreme event, the loss of livestock was reported when they were struck by floods (9%), avalanches (9%), landslides (4%), erratic rains (4%), and heavy snowfalls (3%). In recent years, more and more children are enrolled in schools. They also attributed the growth in literacy to the decline of livestock farming as children are in schools and cannot help families in livestock raising. Young and educated people prefer to pursue off-farm jobs and occupations over livestock keeping and emigrate to urban centers within the country or in other countries.

In addition, the cultivation of cash crops (e.g., potatoes, peas, tomatoes) in Karimabad and Garam Chahsma valleys have expanded, which have little fodder value for the livestock. Farmers cannot cope with the acute shortage of fodder for the animals during the winter season thus reducing their livestock. Similarly, the recent trend of young people moving to urban centers for education and labor work results in a shortage of manpower for livestock management. Most of the livestock is now raised to meet the basic daily dietary needs of the households, instead of earning income by selling it in the market although still practiced by some households. The selected views on livestock practices are the following:

> *"Livestock is declining, it almost has ended because it requires human resources. Because of education, colleges, and universities, people are unable to continue it. That is why agriculture is also compromised ... If I recall my childhood or if I talk about 2000 or before, people used to have livestock, sheep, and goats. In our house, the elders who were illiterate used to take them for grazing on mountains and pastures there. But when it came to the new generation, schools were built and people started going to schools. Then there was a gap between the old and new generations. Then this work [livestock rearing] was*

> *not done, then all those were sold out. Livestock depleted. Now every household has one or two cows for milk, which people mostly use for tea."* (Interview, Shershal village, June 2020)

The decline in livestock deprives households of cash income and also weakens household food security. Farmers also highlighted that alpine pastures are declining in the area because of their over-exploitation, and they are reducing livestock to *"protect them and do planning for them"* for their restoration. To reduce the risk of erosion and degradation of rangelands, a joint initiative is undertaken by several villages, especially in Garam Chashma valley, to reduce the number of animals so that less grazing land is destabilized. Such initiatives are advocated by development organizations to reduce the impact of floods and landslides on the rangelands. Despite a reduction in livestock farming, it still plays a significant role in the food security of local populations.

9.5 Discussion

Our study explores the relationship between climate change and human (im)mobilities in the Lotkuh Valley in the Eastern Hindu Kush, using a mixed methods approach. We revealed that approximately two-thirds of surveyed households reported migration, while more than the half reported involuntary immobility of at least one of their members. Both groups are predominantly men. However, the qualitative data showed that the migration of young women has been increasing recently in several villages of Lotkuh Valley, primarily for educational aspirations and later acquiring jobs in major urban centers. These findings are in line with the global trend of increased feminization of migration observed in recent years (Malhotra et al., 2016).

The primary drivers of both mobility and immobility are socioeconomic. However, the added burden of recurring extreme events results in specific manifestations of mobility and immobility, which is consistent with the Foresight framework (Black, Adger, et al., 2011). These events, such as floods and earthquakes, often lead to forced displacement (Adger et al., 2018) which is short-term and short-distance and often unforeseen involuntary movement triggered by rapid onset events. In such scenarios, extreme events act as push factors causing forced displacement. Meanwhile, social networks in places of destination, coupled with higher income and employment opportunities, serve as the pull factors significantly influencing migration decisions (Sherbinin et al., 2022).

Furthermore, our research reveals that climate (im)mobilities manifest through the interplay of climate change and associated natural extreme events with livelihoods. This manifests in the form of land degradation, decreased crop productivity, and a decline in livestock farming. Extreme events exacerbate soil erosion and degrade the fertile farmlands along riverbanks through inundation and debris deposition. This land loss contributes to food insecurity among affected households, also observed in the HKH region (Gioli et al., 2019; Hussain et al., 2016). Additionally, another process that was noted by farmers in Parsan is the landslips or subsidence caused by the destabilization of the land triggered by the absorption of large quantities of water seeping into the land mass (Ali et al., 2017). When lands are severely affected and the restoration costs are not met, some households are compelled to abandon their lands, as also observed in the wider HKH region (Rasul et al., 2019).

In the context of our study, it is evident that extreme events exacerbate the financial constraints faced by households, thereby leading to the immobility of their members (Hoffmann et al., 2020). These individuals often lack migration capabilities (De Haas, 2021; Maharjan et al., 2021) such as the necessary financial resources to pursue migration to preferred destinations, whether within the country or internationally. Moreover, for certain households, a strong attachment to their land emerges as a contributing factor to voluntary immobility, a sentiment highlighted by Adams (2016). Additionally, some individuals express a sense of compulsion to remain in their villages – involuntary immobility (De Haas, 2021; Zickgraf, 2021b), emphasizing the multifaceted nature of factors influencing immobility in this region (Boas et al., 2022; De Haas, 2021).

Similarly, crop productivity in the Lotkuh Valley experiences adverse impacts from a combination of extreme events, shifts in temperature and precipitation patterns. The impacts of extreme events include a reduction in agricultural yield due to the disruption of standing crops, irrigation, and other infrastructure which are also reported in other studies in the HKH region (Hussain et al., 2018; Nizami et al., 2019; Rasul et al., 2019). The restoration of irrigation channels requires a lot of community effort and costs (Nüsser, 2001) which further strains the household income. In addition to the extreme events, changes in precipitation and temperature patterns have negative consequences on crop yields in the region, confirming the findings documented in various areas of the HKH (Hussain et al., 2016; Rasul et al., 2019). Furthermore, it was noted that certain households placed greater emphasis on the impact of extreme events on both crop yields and labor migration, showing a stronger association compared to shifts in precipitation and temperature. This observation aligns with the results of a study conducted in the HKH region (Banerjee et al., 2011). As a result, households turn to labor migration as an adaptive strategy to diversify their income and reduce the risk of food insecurity (Black, Bennett, et al., 2011; Call & Gray, 2020), which is consistent with NELM and livelihoods framework (Scoones, 1998; Stark & Bloom, 1985). In contrast, households facing severe income stress and erosion of economic assets find themselves in a situation where their members are compelled toward immobility despite aspiring to migrate, which reflects involuntary immobility due to high migration aspirations and low migration capabilities (De Haas, 2021).

Additionally, the decline in livestock farming in the Lotkuh valley can be attributed to a confluence of factors. These include the aspirations of young individuals seeking opportunities for education, off-farm employment in urban centers, an urban lifestyle, and a shift to cash crops, as well as the implementation of risk reduction measures aimed at addressing the degradation of rangelands and erosion stemming from flash floods and landslides. Finally, the decline in farming partially due to migration aspirations results in the loss of vital income and reduces household food security in the long-term often leading to further immobility and mobility of household members. Also, our results confirm the decline in livestock and its drivers noted in previous studies (Nüsser et al., 2012).

Largely, the households in the Lotkuh Valley tend to adopt a mixed strategy, where certain members engage in out-migration as part of an adaptive approach by moving to various urban cities or other countries. Meanwhile, others opt to remain in their places of origin, continuing their engagement in agricultural activities and fulfilling their social roles. This strategy is a widely chosen livelihood diversification measure aimed at mitigating losses and alleviating economic stress, also noted in other studies in the neighboring regions (Banerjee et al., 2011; Gioli, Khan, & Scheffran, 2014; Maharjan et al., 2020; Siddiqui et al., 2019). Migration as an adaptive strategy by the households in the face of land degradation, decreasing crop productivity, and declining livestock farming in Lotkuh Valley is aligned with the foresight and livelihoods frameworks (Black, Adger, et al., 2011; Scoones, 1998). Moreover, migration decision-making is undertaken at the household level aimed at improving the socioeconomic status of the household in line with the NELM theory (Piguet, 2018; Stark & Bloom, 1985). However, the power and gender dynamics that influence the (im)mobility, as well as the effectiveness of migration as an adaptation strategy require further research.

9.6 Conclusion

This study sheds light on the intricate relationship between climate change, environmental factors, and human (im)mobility in the Lutkoh valley of the Eastern Hindu Kush. Our findings emphasize that while socioeconomic factors are primary drivers, climate change and associated natural extreme events play a crucial role in shaping the specific manifestations of mobility and immobility outcomes. Extreme events such as floods trigger forced displacements in risk-prone areas (Adger et al., 2018).

Climate (im)mobilities are the result of a complex interplay between climate change, extreme events, and local livelihoods. We identified the impacts of climate change and extreme events on land resources, crop productivity, and livestock farming as the three aspects of livelihoods that influence mobility and immobility outcomes in the Lotkuh Valley. Specifically, extreme events, such as flash floods and landslides, exacerbate soil erosion and loss of fertile farmlands, contributing to food insecurity and pushing households toward labor migration as an adaptation strategy. For those with severely stressed incomes and eroded economic assets, immobility is the outcome as they do not possess enough capabilities to undertake migration. It is also evident that some households pursue a mixed strategy (Gioli, Khan, Bisht, & Scheffran, 2014; Maharjan et al., 2021) by sending member(s) of the household to other areas while others stay to pursue livelihoods in places of origins. With climate change and its influence on the frequency and intensity of natural hazards in the Hindu Kush Himalaya (Wester et al., 2019), the climatic and environmental conditions may further exert pressure on mountain livelihoods affecting existing mobility and immobility patterns in the region.

We contribute to the debate on the relationship between climate change and human movement by applying the concept of 'climate mobilities' (Boas et al., 2019; Boas et al., 2022; Cundill et al., 2021) to the setting of Eastern Hindu Kush and addressed the gap in the understanding of how climate change is affecting human movement in the area. Our study provides a more nuanced and holistic understanding of the complex ways in which climate change is shaping patterns of human mobility and immobility. Moreover, the findings have practical implications for policymakers, government, and development organizations by informing their livelihood and disaster risk reduction strategies and programs to address the challenges of land degradation, reduction in crop productivity, and decline in livestock farming.

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SYNTHESIS

10. Synthesis of Results

10.1 Integrated Assessment of Climate Change and its Impacts

The first aim of this doctoral thesis is to investigate climate change and natural hazards, along with their impacts on mountain livelihoods in the Eastern Hindu Kush region. This aim seeks to explore the perceptions of local people regarding climate change and analyze its impacts on their livelihoods. Furthermore, this aim strives to offer an integrated assessment of climate change by juxtaposing local perceptions with the trend analysis of climate data. This synthesis section aims to integrate and synthesize the findings from multiple research papers conducted within the scope of this aim.

To achieve a comprehensive understanding of the research questions posed for this aim, multiple facets were examined. The first question focused on the perceptions of climate change by local people in the Lotkuh Valley and the subsequent impacts on their livelihoods. Through a mixed methods approach which involved household survey, interviews, and focus groups, data were collected to unravel how climate change was perceived and experienced by the local people. The household survey indicated that most of the respondents perceived that climate has changed over the last two decades (2000-2019). Most of the survey respondents reported that both temperature and precipitation have changed over the past twenty years. Similar perceptions of changing temperature and precipitation are also noted in the Rakaposhi Valley of Gilgit-Baltistan (Bhatta et al., 2019). Further manifestations of climate change at the local level included a rise in winter and summer temperatures, thus confirming the previous studies in the Indus basin (A. Hussain et al., 2016; Joshi et al., 2013). Regarding the change in the length of seasons, on the one hand, an increase in summer duration was perceived, and on the other hand, a decrease in winter duration was reported, also confirming such perceived changes in Gilgit-Baltistan (Joshi et al., 2013).

Concerning precipitation changes, people perceived an increase in overall rainfall with changes in rainfall patterns in different seasons. A recent shift from rainfall maximum in spring to summer was also noticed. Summer rainfall, also associated with monsoons, is perceived as a relatively new phenomenon in Lotkuh Valley. Moreover, participants perceived a decline in snowfall over the past two decades, also in agreement with perceptions in the Booni in Upper Chitral (Ajani & van der Geest, 2021), and Pamir region (Haag et al., 2021). As far as the intensity of precipitation events is concerned, a decrease in snowfall intensity and an increase in rainfall are observed.

The mountain livelihoods in the Lotkuh Valley, which are dependent on natural resources, are affected by the changing weather patterns (Nüsser et al., 2019; Parveen et al., 2015). Qualitative data collection methods (interviews and focus groups) were used to assess the implications of climate change for local livelihoods. People associated changes in weather patterns and altering seasonal duration with low crop productivity. It was observed by local people that the warming causes the early ripening of crops which results in smaller grain size as well as the premature drying of crops. Another factor that affects agricultural production and crop yield is the changes in the onset of the seasons and the emergence of crop pests and diseases. Changes in the seasonal patterns are also causing shifts in the harvest period in the studied villages. The agriculture in the Lotkuh Valley depends on glacial and snow melt water which is becoming more unpredictable due to changes in the cryosphere (Nüsser, 2017; Nüsser et al., 2019). Moreover, communities noted that the changes in precipitation patterns affect water availability in the Lotkuh Valley. Communities highlighted that the snowfall is on the decline in the area including its duration, extent, and depth. The reduction in snow precipitation and warming seasons leads to its earlier melting and triggers water scarcity in some areas during the summers (Arias et al., 2021). People also noticed shifts in rainfall patterns with more rain now concentrated in summer than the spring. The summer rains are associated with monsoon precipitation which is a relatively recent phenomenon in the Lotkuh Valley. People also regard rainfall in spring to have positive outcomes for their agriculture as it complements their irrigation needs. On the contrary, summer rainfalls are intense and disrupt the standing and ready-to-harvest crops, often leading to crop failure, thus having severe negative consequences for local livelihoods. Intense monsoon rainfall also contributes to the flood and landslide risk in the valley which also impacts crops and their productivity. People also noted that the intense snowfall events when combined with the earthquakes cause avalanches which affect human lives and livestock. Overall, farmers also noted the variability of rainfall and temperature over the years. For instance, the year 2020 was a dry and hot year in which the yield of wheat crops was severely reduced. Other years have intense rainfalls in summers or springs often coupled with hot weather leading to floods and landslides. More discussion on natural hazards (including multi-hazards) and associated extreme events and their impacts on mountain livelihoods is provided later in this chapter.

After providing a brief synthesis of perceptions of climate change and its impacts, it is important to investigate what are the factors that shape these perceptions. This question has been explored in several other studies in different other regions (Lujala et al., 2015; Poortinga et al., 2019; Sloggy et al., 2021; Weber, 2016; Xie et al., 2022), but not in the Eastern Hindu Kush region. Since a household survey was employed to gather data on the perceptions, related socioeconomic and demographic variables were used to assess their influence on climate change perceptions using a logistic regression model. The independent variables included in this model are gender, age, education, farmers, household size, agricultural income, monthly income, ownership of land, and finally if they are affected by an extreme event in the past. The regression results showed that only three variables (no education, land ownership, and those affected by extreme events) are significant. The respondents who have no education compared to the educated are less likely to perceive climate change. The respondents who have agricultural land are more likely to perceive climate change. Finally, people who are affected by an extreme event are also more likely to perceive climate change (Gioli, Khan, & Scheffran, 2014).

The next research question focused on analyzing trends in climate data (i.e., temperature, precipitation, and snow), and then comparing it with the local perceptions in the Lotkuh Valley. A major obstacle in climate data analysis in the research areas is the low density of climate stations in this complex high mountain region of the Eastern Hindu Kush similar to the neighboring regions in the HKH (Haag et al., 2021; Zandler et al., 2019). The climate parameters such as Tmax, Tmin, and precipitation were analyzed using the monthly data obtained from the Chitral Weather Station from 1970 to 2019. However, we used the reanalysis datasets ERA5-Land for climate trend analysis to overcome the insufficient temporal resolution coupled with challenges associated with station data in the peripheral high mountain regions in the HKH (Muñoz Sabater, 2019). Moreover, the previous studies (Baudouin et al., 2020; Zandler et al., 2020) in the region confirmed the increased performance of reanalysis datasets compared to other climate data sources close to the research area and with similar conditions. Snow trends were derived from the analysis of the daily MODIS Snow Cover Product for the period 2001-2019. Our results show that annual temperature trends (mean temperature, minimum, and maximum) from 1970 to 2019 are increasing in our research area. The winter season was characterized by a warmer Tmax and a reduction in frost days, whereas the summer season did not exhibit a temperature trend. For precipitation, no significant trends were found which is also similar to other studies in the region (S. Ahmad et al., 2020; S. Ahmad et al., 2021). Similarly, MODIS data did not show any significant trend in snow cover similar to other regional studies (S. Ahmad et al., 2020; S. Ahmad et al., 2021) which do not show conclusive trends. Overall, our research matches the station data with existing climate research in the region and brings confidence to ERA-5 for its use in the Eastern Hindu Kush. Upon juxtaposing the climate trends and local perceptions, it can be noted the agreement on annual temperature rise whereas no significant trend in annual precipitation in the climate data. Similarly, there is divergence on the snow trends where perceptions indicate a decreasing trend while MODIS data show no significant trend. Similarly, climate data showed a decrease in the frost days in convergence with decreasing winter duration noted in perceptions. Furthermore, perceptions indicate that the summer duration is increasing whereas the climate data show no significant trend in summer days. Finally, the above discussion so far shows the convergence as well as divergence between local perceptions and climate data trends, but their integrated assessment can complement each other and provide a holistic understanding of climate assessment.

The last three questions within the first aim explored natural hazards and their impacts on local livelihoods and land cover. To begin with natural hazards and their impacts on mountain livelihoods in the Lotkuh Valley, a mixed method research design comprising household survey, interviews, and focus groups were employed, as mentioned earlier in this section. The results show that Lotkuh Valley is highly susceptible to the multi-hazards. These hazards trigger connecting and compounding extreme events in the valley. Floods, landslides, and earthquakes are widely present throughout the study area. Earthquake, which is one of the major recurring geological hazards in the Hindu Kush further triggers landslides and avalanches and exacerbate their impact on the livelihoods. Heavy snowfall and rainfall events affect households in several studied villages. Flooding is the predominant and most common hazard in the area which affected the greatest number of households in the Lotkuh Valley, confirming other studies in the HKH region (D. Ahmad & Afzal, 2020; Ajani & van der Geest, 2021; M. Hussain et al., 2019). The area is prone to both riverine and flash flooding. Furthermore, the results show that floods affected all the surveyed villages, except Shershall in the past decade.

Most of the villages are prone to the multi-hazard phenomenon, i.e., when a community is exposed to the risk or more than one hazard type. Our case study shows that all of the thirteen villages surveyed are exposed to the impacts of at least three or more different types of natural hazards. Analysis of our results shows that nine villages (out of thirteen villages) experienced at least five types of hazards, while four villages, i.e., Roi, Wakht, Shut, and Zhitur experienced at least eight types of hazards. This analysis sheds light on how vulnerable the populations are living in these villages and requires a diverse set of risk reduction and adaptation measures. In terms of the impacts of the extreme events on people and their livelihoods, avalanches have caused relatively more loss of human lives and injuries compared to other events. Earthquakes, floods, avalanches, and landslides have damaged or destroyed the housing infrastructure in the area. Irrigation-dependent agriculture is also severely affected in areas where extreme events disrupt the irrigation networks and loss of agricultural land. The irrigation infrastructure runs through talus cones and scree slopes making them prone to the impacts of landslides, rockfalls, avalanches, and flash floods (Nüsser et al., 2019; Parveen et al., 2015; Vaidya et al., 2019b). The findings of our research show that floods have a devastating impact on agricultural land and standing crops. Urbanization, i.e., expansion of the housing infrastructure and cultivation of the lands along the riverbanks make them vulnerable to flood impact (Hewitt & Mehta, 2012). It was also noted that the severity and potential risk to people's lives and livestock cause ex-ante and ex-post displacement from the hazard-prone areas.

Land cover is one of the key elements in the natural environment which is affected by natural hazards and various extreme events in addition to anthropogenic activities (Masson-Delmotte & Pörtner, 2022; Nüsser, 2001). To investigate this aspect, a time series approach using the Landsat data in the Eastern Hindu Kush was used to examine the abrupt change in the land cover from 1988 to 2019. BFAST method was utilized to analyze the abrupt change (or breakpoint) in the trend component of the time series analysis particularly due to its robustness against the persistent noise and strong seasonality in the data (Verbesselt et al., 2010). In this research approach, vegetation cover in the valleys was focused which is where most of the settlements are located, including the farmland. We used MSAVI which is appropriate for the region as it can minimize the soil background effects widely present in the arid and semi-arid environmental conditions.

The results show that the majority of the pixels in the valleys experienced breakpoints, or abrupt change during the past three decades. This implies that the vegetation cover experienced extensive abrupt change. It was observed that the upper catchments experienced more breakpoints compared to the lower catchments possibly due to their high exposure to the flash floods. Large chunks of the pixels with breakpoints are aligned along the waterways such as rivers, and streams (locally called *gol*), and show spatial patterns of flooding. The upper parts of the catchments are exposed to heavy precipitation and glacier melting thus prone to flash floods while the lower catchments experience inundation of the floodplain (Ashraf et al., 2021a; Shaw & Nibanupudi, 2015). The fieldwork provided valuable insights that confirmed high sediment transport noticed in the flash flood-affected areas of Kalash and Lotkuh valleys. On the contrary, the lower catchments are more susceptible to riverine flooding triggered by overflows in rivers which further impact the crops, lands, infrastructure, and human lives in the floodplains.

The analysis of catchment trends reveals decreased trends for summer, autumn, and winter in all catchments. However, mixed trends are noticed for the spring season, with two catchments (Panjkora and Swat) showing increasing trends and two others (Bashgal and Kandia) exhibiting no trend. The upward trend in some catchments may be attributed to different climatic conditions, such as higher rainfall and distinct vegetation patterns in the southern part compared to the rest of the study area. The diverse climatic conditions of the Chitral catchment, with varying rainfall in the north and south, might also contribute to different seasonal trends. Overall, the declining annual trend can be linked to decreasing annual rainfall trends in the Upper Indu Basin, consistent with other hydrometeorological studies (Latif et al., 2018; Yaseen et al., 2020). On the other hand, the increasing trend in the spring in certain catchments is likely influenced by rising temperatures, leading to greater glacial and snowmelt during that period (Baig et al., 2021; Shahid & Rahman, 2021).

It is crucial to assess the potential drivers of abrupt change in land cover in the Eastern Hindu Kush region. This phenomenon is caused by a combination of anthropogenic interventions and natural factors. The impact of human activities on land cover is significant, primarily driven by urbanization, which encompasses the construction of extensive road networks, clear-cutting of forests, and the abandonment or redevelopment of land in the area.

The complex climatology of the Hindu Kush region where a multitude of local and regional climatic conditions play a significant role in shaping events that affect the land cover throughout the various seasons. This thesis does not determine the precise drivers of these seasonal peaks, as they necessitate a sophisticated climatological approach that falls beyond the scope of this study. However, in general, the occurrence of summer events can be attributed to extreme monsoon rainfall, which is influenced by the Madden Julian Oscillation, Indian Ocean Dipole, and indirectly by EL Niño Southern Oscillation (Gadgil et al., 2004). On the other hand, winter and spring events are influenced by the Northern Atlantic Oscillation and the Siberian High (F. S. Syed et al., 2006). Moreover, spring events may be caused by heavy snowfall in previous winter and the early melting of glaciers and snow in spring (S. Ahmad et al., 2020; Shahid & Rahman, 2021). Additionally, intense summer events are linked to a strong summer monsoon (Webster et al., 2011). Interestingly, the year 2010, which experienced a robust monsoon, exhibited comparatively lower abrupt changes during the summer season.

Recurring floods are the primary natural hazards that drive the abrupt change in the land cover in the valleys. Other natural hazards such as landslides, and boulder falls are difficult to identify due to their smaller spatial impact compared to floods. Some of the major flooding events such as floods in Ayun, Rumber, and Kalash valleys as well as in Lotkoh Valleys were detected which had large coherent spatial patterns along the riverbanks. To do so, BFAST results and a mixed approach, combining visual interpretation, historical imagery, and fieldwork, were utilized to trace the timing and extent of specific flood events in the study area. Major breakpoints aligned with historical floods, but numerous isolated breakpoints lacked corresponding records, likely due to challenges in detecting natural hazards like rockfalls and landslides, as well as potential anthropogenic triggers such as deforestation and slope undercutting.

In addition to using the BFAST method to detect the abrupt change and floods as its drivers in the Eastern Hindu Kush region, it was also applied to examine vegetation dynamics in the Northwestern Highlands of Ethiopia (as described in Manuscript III). MODIS-derived NDVI time series dataset was analyzed to identify abrupt changes in the vegetation. This analysis included determining the number of breakpoints, their direction, and their magnitude. The results were then integrated with a seasonal trend analysis conducted using TIMESAT, serving as key indicators for ecosystem analysis. The findings suggest that the ecosystem condition improved due to plantation activities. This research highlights the utility of combining the BFAST approach for abrupt change detection with other methods to comprehensively study vegetation dynamics in an area.

10.2 Climate (Im)Mobilities in Mountain Communities

The second research aim of this doctoral thesis is to gain a comprehensive understanding of climate (im)mobilities in the Lotkuh Valley, with a particular focus on exploring the interrelations between climate change, the environment, and drivers of (im)mobilities. This synthesis section describes the multitude of factors influencing migration patterns and immobility decisions in the context of a changing climate and environment. By analyzing migration characteristics, key drivers, and the impact of climate change on economic conditions, this section seeks to shed light on the complexities of human mobility and immobility in response to environmental challenges. To answer this aim, a mixed methods approach comprising a household survey, interviews, and focus groups in the sampled villages was utilized. The methodological approach provided both qualitative and quantitative data to explore different aspects of climate (im)mobilities. Conceptually, the study is embedded in several migration-related theories such as push-pull (Sherbinin et al., 2022), NELM (Stark & Bloom, David, E., 1985), aspirations and capabilities framework (De Haas, 2021), livelihoods approach (Natarajan et al., 2022; Scoones, 1998), and Foresight framework (Black, Adger, et al., 2011).

Under this aim, the first research question seeks to identify and analyze the mobility patterns prevalent in the Lotkuh Valley and then explore the key drivers of mobility and immobility decisions in the Lotkuh Valley. The survey results show that over three-quarters of surveyed households have reported migration of at least one of their members during 2010-2020. Immobility was reported in more than half of the surveyed households and similar gender dynamics as for the migration. The majority of the migration is taking place to other cities, particularly the major urban centers in Pakistan. Moreover, the migration trend is from rural to urban areas. Temporally, most of the migration is temporary in which migrants engage in labor work, and seek education or other employment opportunities in the urban areas. Seasonal migration is also taking place, although less than those in temporary migration, mostly concentrated in the winter season. Permanent migration is also taking place where migrants settle permanently in the urban centers. Furthermore, the findings show that there is a similar distribution of characteristics such as age, gender, and educational attainment between migrant and non-migrant (with immobility) groups. However, it is worth noting that the destinations differ significantly for these two groups, i.e., a higher proportion of the immobility group aims to move internationally as compared to the migrant group. Whereas a higher proportion of the migration group moved to other urban centers within the country compared to the immobility group. This difference highlights the issue of high aspirations in terms of choice of international migration destinations but lack of capabilities resulting in their immobility.

The gender dynamics of the mobility patterns in Lotkuh Valley are changing due to the feminization of out-migration, though not everywhere but the number of young women moving to other cities is on the rise. This is more attributed to the pursuit of higher education for women, particularly in the nursing profession which is also supported by the social networks present in the cities as well as support in terms of loans and admission from the Aga Khan Development Network, which is a major development actor in the region. The migration of women is significantly higher than in the neighboring valleys of Hunza and Yasin in the Gilgit-Baltistan region (Gioli, Khan, Bisht, & Scheffran, 2014). The reasons could be the relatively stronger social networks of Lotkuh Valley in the destination area as well as the difference between the time of both studies.

Overall, the results show that there are multiple drivers of both migration and immobility in the Lotkuh Valley. Socioeconomic motives are predominant including employment opportunities, higher income, and better access to educational and health services at the destinations as key drivers of migration. As mentioned earlier, migrants' social networks and family connections at the destinations contribute to the migrants' choice of these destinations.

Finally, displacement is another mobility pattern that is triggered by extreme natural events in the area. A large proportion of the surveyed households reported displacement due to extreme events during the past decade. Floods, earthquakes, and landslides are the predominant hazards that trigger displacements. The severity of the risk and likelihood of loss of human life, livestock, and other valuable assets are the crucial factors that influence the displacement. Displacement, or escape mobility is generally short-term and ranges from a couple of days to a couple of weeks and is taken over a short distance such as a safe place in the nearby area or other adjoining valleys. The displacement episodes are both ex-ante and ex-post extreme events and are managed by communities themselves with the help of NGOs and the government providing food rations and shelters in case of major catastrophic events.

The second question under this research aim explores how extreme events and climatic changes affect mountain livelihoods influencing different mobility and immobility outcomes. The livelihoods in the mountain communities of Lotkuh Valley are based on subsistence agriculture and livestock farming but also coupled with labor income. The analysis of our findings shows that climate (im)mobilities are linked with livelihoods through land degradation, decline in crop productivity, and livestock farming. Land is scarce and considered an important livelihood resource by the local people in the Lotkuh Valley. It is highly susceptible to the impacts of climate change and various extreme events. A multitude of natural hazards including floods, landslides, rockfall, and avalanches cause erosion and degradation of the land in the area. The study results show that floods, landslides, and avalanches are the key drivers of land degradation as they deposit debris and sediments, and also cause erosion of fertile topsoil. Most of the farmland is situated along the riverbanks in the floodplain, and the recurring floods cause its erosion. The rehabilitation of the affected land requires financial resources which are often beyond farmers' financial capacity. Some parts of the affected lands cannot be restored due to such reasons and are not cultivable anymore, contributing to the issue of land abandonment also reported in other parts of HKH (Rasul et al., 2019). Moreover, soil erosion and land degradation are crucial factors in the local livelihoods context as they adversely affect the food security and income of the households. To cope with this economic strain, the households engage in labor migration to urban centers. It is often a mixed strategy in which some household members undertake migration whereas others continue to work in agriculture (Gioli, Khan, Bisht, & Scheffran, 2014; Kreutzmann, 2012a; F. Rahman, 2007). Some households, although present in fewer numbers, pursue labor migration and lend their lands to other people in the village when they do not find them economically viable.

10.3 Research Framework

In the pursuit of understanding the complex interplay between climate change and human (im)mobility in the Eastern Hindu Kush region, the third aim of this thesis endeavors to develop an interdisciplinary framework. This framework, as shown in Figure10.1, serves as a foundational structure that underpins this entire thesis, contributing significantly to the discourse surrounding the complex interrelationship between climate change and human (im)mobility (Cattaneo et al., 2019; Piguet, 2022; Piguet et al., 2018). The primary objective of this research framework is to provide a comprehensive and holistic approach to analyzing the multifaceted relationship between climate change and human mobility in the Eastern Hindu Kush. By combining findings and methodologies from the manuscripts, this framework aims to offer a structured and nuanced lens through which to examine this intricate and complex relationship (Miller & Vu, 2021; Piguet, 2022).

The research methodology in this framework combines a range of approaches, including both qualitative and quantitative data collection and analysis. Moreover, the overall approach is interdisciplinary and suited for exploring the complexity of climate change and human mobility nexus. On the one hand, the framework lays a top-down approach entailing remote sensing and downscaling methods to collect and analyze biophysical data (temperature, precipitation, snow, and vegetation). Biophysical data was analyzed using time series analysis and trend analysis methods. On the other hand, the bottom-up approach comprises collecting and analyzing social data (perceptions, impacts, socioeconomic, individual, and household characteristics) using social science-based methods. This data was mixed so included both qualitative and quantitative methods such as household survey, semi-structured interviews, and focus group discussions in the sampled villages. The quantitative data was analyzed through descriptive statistics and regression model, while qualitative data were analyzed using qualitative content analysis. In addition, the framework shows that the data was collected and analyzed at different spatial scales, for instance, the multi-hazards and their impacts were analyzed at the local scale (mainly at the village level) while the changes in temperature and precipitation were analyzed using downscaling approaches on regional products. Overall, the empirical foundations of this framework are rooted in the results and methods described in the manuscripts of this thesis.

The research framework shows that a range of factors influence the mobility and immobility outcomes in our study region. The impacts of climate change and multi-hazards adversely affect local livelihoods particularly agricultural productivity, livestock farming, and land resources which then influence mobility and immobility outcomes. Moreover, political, economic, social, and environmental factors shape local livelihoods and also influence the (im)mobility outcomes. The (im)mobility outcomes include migration forced displacement, and involuntary immobility which were explored in the context of this thesis. However, other forms of mobility may also exist.

The strengths of this research framework include its comprehensive approach that combines qualitative and quantitative methods, encompassing both the social and physical dimensions of climate change and (im)mobility, offering a comprehensive understanding of the climate change mobility nexus. Furthermore, this framework can be adapted and applied to other mountain regions facing similar challenges, offering further opportunities for comparative research. The framework also enables the integration of data from different sources and disciplines, fostering interdisciplinary collaboration in the study of climate (im)mobilities. Hence, the framework is particularly pertinent to interdisciplinary research on the nexus of climate change and human mobility and the mixed approach (Bazeley, 2018; Creswell & Clark, 2017; Tashakkori & Teddlie, 2021), as it necessitates the utilization of diverse research methods and techniques to unravel the complexities and develop a holistic understanding of the subject (Piguet, 2022). However, the framework also has certain limitations. It relies heavily on different types of data, which can be a limiting factor in some regions, and combining qualitative and quantitative data also poses integration challenges. Nevertheless, the framework can be advanced by developing more sophisticated spatial analysis techniques to capture complex dynamics of climate change and human (im)mobility at different scales (Miller & Vu, 2021; Piguet, 2022).

10.4 Implications of the Research

The implications of this research are significant and span multiple domains, including environmental, social, and policy aspects, due to the wide range of topics covered in this dissertation. Here are some of the key implications based on the research findings:

10.4.1 Environmental implications

- The research underscores the ongoing impacts associated with climate change in the Eastern Hindu Kush region, including rising temperatures, shifting precipitation patterns, and changing snowfall trends (Raghavan Krishnan et al., 2019). However, these changes were prominent in the local perceptions while increasing annual temperature trends and warmer winters were only significant. Nevertheless, these changes have implications for the local environment, affecting ecosystems, water resources, and the cryosphere (Ebi et al., 2021; Nie et al., 2021).

- The study highlights the region's vulnerability to a multitude of natural hazards, including floods, landslides, earthquakes, and avalanches. Hydrometeorological hazards are exacerbated by climate change and can lead to significant environmental impacts, including land degradation (Hewitt & Mehta, 2012; Vaidya et al., 2019a).

- The research also shows that land cover changes in the region are extensive, with a high proportion of the area in the valleys experiencing abrupt changes over the past three decades. These changes can have adverse effects on local environmental conditions such as ecosystems, hydrology, and soil stability.

10.4.2 Social implications

- The research reveals that many residents of the Lotkuh Valley perceive climate change and have observed its effects on agriculture, water availability, and extreme events. Understanding local perceptions of climate change and its impacts is crucial for effective climate change adaptation at the local level.

- Furthermore, the findings of this research suggest that local livelihoods in the mountain communities of the Lotkuh Valley are highly susceptible to the impacts of climate change and various natural hazards. Crop productivity, livestock farming, and land resources are at risk, leading to economic challenges for the local populations.

- The research offers valuable insights into migration patterns, with a significant portion of the local population engaging in migration to urban areas. Gender dynamics in migration are changing, with more young women moving to cities for education and employment opportunities. Moreover, the economic stress caused by the impacts of climate change and natural extreme events also leads to the immobility of household members who have migration aspirations but lack the capabilities. Furthermore, it is important to note that extreme events, such as floods, earthquakes, and landslides, are causing forced displacement. Understanding these mobility and immobility patterns is crucial for promoting sustainable livelihoods in the area.

10.4.3 Policy and adaptation implications

- The research emphasizes the importance of integrated assessments that combine scientific data, local perceptions, and community knowledge to understand the impact of climate change as well as extreme events comprehensively. This can inform effective adaptation and risk reduction strategies.

- Policies and interventions should focus on enhancing the resilience of local livelihoods in the face of climate change and multi-hazards. This includes formulating strategies for sustainable agriculture, water resource management, early warning systems, and infrastructure resilience (Mishra et al., 2019; Tsering et al., 2021; Zia & Wagner, 2015).

- Policies should recognize the role of migration in enhancing educational and employment opportunities by focusing on improving access to quality education and skill development programs in the areas of origin to equip individuals with the capabilities to migrate when needed.
- As more and more women in the region are engaging in migration, policies should be gender-sensitive by considering gender-specific challenges and opportunities in education and employment opportunities.
- Finally, longitudinal studies can provide insights into the dynamics of migration and immobility over time, and unravel various drivers that influence these dynamics.

10.5 Limitations of the Study

While this research has provided valuable insights into the complex relationship between climate change, natural hazards, and human mobility in the Eastern Hindu Kush region, it is essential to acknowledge its limitations as is the case with research. First, the study relied on data collected from a specific set of villages within the region, which might not fully represent the diversity of experiences and perspectives across the broader area as the village selection was purposive and only from the Lotkuh Valley.

Additionally, the study had different temporal scales which were constrained by the availability of various datasets. For instance, the temporal scale for local perceptions, the temporal scope of twenty years, which mainly covers the period from 2000 to 2019, might not capture long-term trends and could be influenced by short-term fluctuations. Integration across these different scales has limitations.

Furthermore, there were limitations related to data availability and quality, especially in the context of climate and hazard data due to the remote and challenging nature of the study area (Baudouin et al., 2020; Muñoz Sabater, 2019; Zandler et al., 2020). Satellite data such as Landsat contain noise due to cloud and cloud cover shadow in the high mountain regions which may also influence the peak detections for different years.

Local datasets on extreme events and their impacts are scarce and if any then mostly managed by public authorities and access to them is challenging. The same is the case with weather stations which are also scarce, and the data may not present the true climatic conditions due to the complex topography of the region (Baudouin et al., 2020; Haag et al., 2021; Muñoz Sabater, 2019).

It is worth noting that the downscaling of climate data, though a common approach in such regions, comes with inherent uncertainties. Social data, including qualitative and quantitative data, are subject to biases, and while efforts were made to minimize these biases, they may still exist. The participation of women in this research was also limited due to cultural constraints. Nevertheless, where possible they were included in the data collection process.

In this regard, although the research is valuable for the Eastern Hindu Kush region, generalizing findings to other mountain regions or non-mountainous areas may be limited by the unique geography, socioeconomic conditions, and vulnerabilities of the study area.

While this research shows that migration is a prominent adaptation measure to cope with economic stresses, it may not address all the ways mountain communities cope with climate-related challenges. Other aspects of adaptions, for instance coping with water stress (Nüsser, 2017; Nüsser et al., 2019; Nüsser & Schmidt, 2017; Parveen et al., 2015) were not investigated in this research.

It is worth noting that the institutional and governance-related responses to the challenges of climate, environment, and human mobility are underexplored in this research. However, the research discussed certain policy implications.

Finally, the thesis could benefit from further interdisciplinary collaboration, involving experts from various fields such as glacier and snow cover changes, to enhance the understanding of complex climate-mobility interactions.

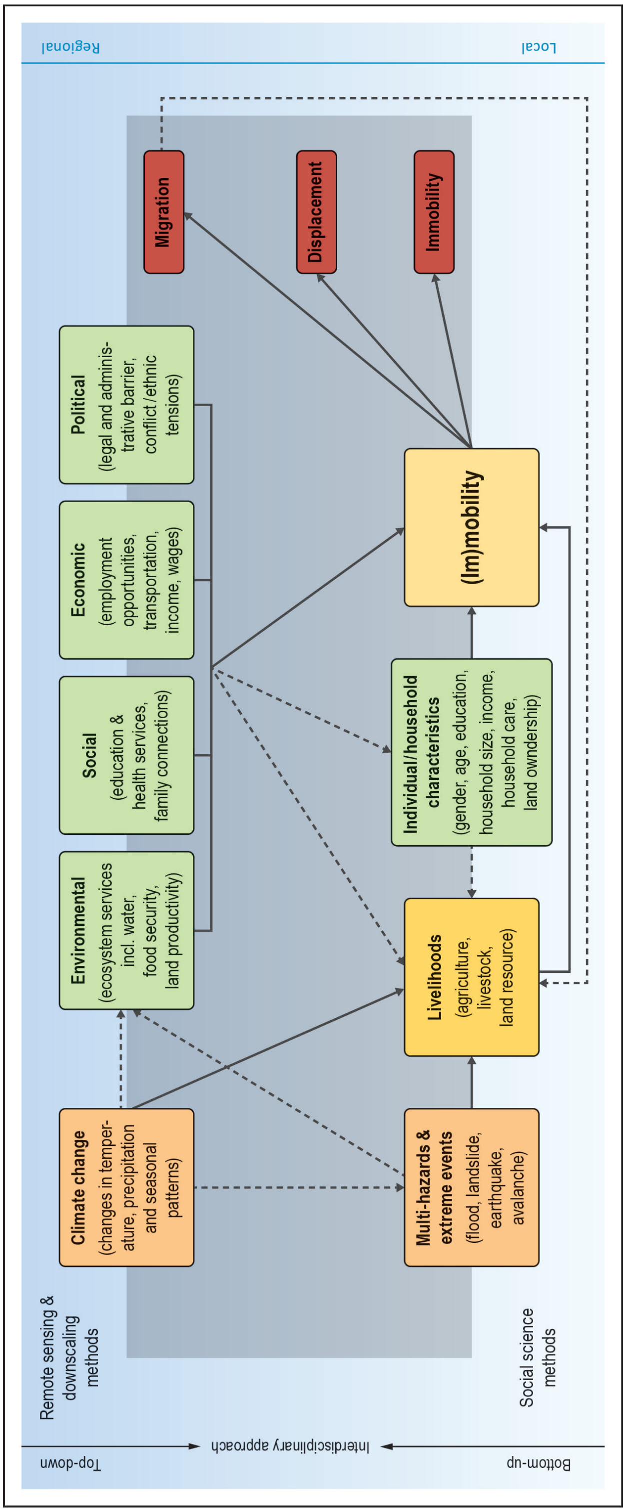

Figure 10.1: An interdisciplinary research framework designed to explore the intricate relationship between climate change, natural hazards (and associated extreme events), and their impacts on human mobility and immobility outcomes.

11. Outlook

As this research has shed light on climate change, natural hazards, and human mobility in the Eastern Hindu Kush, it also paves the way for future investigations. Several dimensions of research merit further investigations. Firstly, it would be important to investigate the ways, other than migration, in which mountain communities, especially in Lotkuh Valley, are adapting to the adverse effects of climate change and natural hazards, particularly land degradation and water resource management. This kind of research will allow researchers and policymakers to develop a comprehensive approach to adaptation measures at the local level.

Additionally, it would be intriguing to explore the interplay between the effects of climate and environmental changes on irrigation management and practices, and the societal structures that shape the water management and irrigation practices (Kreutzmann, 2011, 2023).

Climate immobility in climate mobility scholarship has received attention recently (Boas et al., 2019; Zickgraf, 2018, 2021a, 2021b). Climate immobility remains an underexplored phenomenon in other parts of Eastern Hindu Kush but also the wider HKH region, and it requires further research. Moreover, voluntary immobility (lacking both migration aspirations and capabilities) and its driving factors in the context of climate change also need to be researched in the research area and other regions of HKH. Furthermore, the relationship between extreme events and immobility is also understudied in the HKH region.

Though migration serves as an adaptation strategy in the context of climate change and extreme events, its effectiveness needs to be further explored. This will entail assessing the positive and negative outcomes for both sending households, particularly the negative outcomes for the elderly, women and children, and migrants themselves. These further investigations should contribute to this growing strand of climate migration scholarship on the effectiveness of migration as an adaptation (Szaboova et al., 2023; Vinke et al., 2021).

Expanding the geographical scope of the research on climate mobilities to cover a wider range of communities within the region would allow for more extensive insights. Future studies should also focus on the development of region-specific adaptation and mitigation strategies to address the challenges posed by climate-induced mobility.

Given the dynamic nature of climate change, continuous monitoring, and analysis of climate data, including temperature, precipitation, and cryosphere dynamics, should be integrated into the research agenda. As remote sensing-based time series analysis has shown extensive changes in land cover, newer machine learning methods and approaches to land cover classification (Rußwurm & Körner, 2020; Yan et al., 2019) could provide crucial evidence for formulating specific policies for overcoming the related challenges.

Moreover, exploring the role of policy interventions, institutional governance, and community-based initiatives in shaping adaptive capacities and migration patterns in the region in response to challenges such as water management, offers promising research prospects (Kreutzmann, 2011; Wester et al., 2019a).

Finally, this research has shown that collaborative, interdisciplinary research endeavors in the future are crucial for a holistic understanding of the evolving climate (im)mobility dynamics in the Eastern Hindu Kush region and the development of effective adaptation mechanisms and strategies, for instance, integrated water resource management (Karki et al., 2011), to address the associated challenges (Mukherji et al., 2019).

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Appendix

A. List of the Author's Further Contributions

Conference Presentations/ Talks

1. 2023, Assessing the effectiveness of migration as an adaptive strategy in response to the climate change in the Eastern Hindu Kush, Pakistan, ECMN Network Launch and Conference, University of Vienna, July 10-12.

2. 2021, Natural Hazards and human migration in the Eastern Hindu Kush, northern Pakistan, Colloquium of the Department of Geography, South Asia Institute, Heidelberg University, Heidelberg, Germany, July 5.

3. 2021, Natural Hazards and human migration in the Eastern Hindu Kush, northern Pakistan, Colloquium of the Institute of Geography, University of Bayreuth, Bayreuth, Germany (July 6).

4. 2021, Spatiotemporal analysis of abrupt change in Landsat timer series in the eastern Hindu Kush region, Annual Meeting of the High Mountain Research Group of German Association of Geographers, April 16-17.

5. 2021, Spatiotemporal analysis of disasters in the eastern Hindu Kush region, American Association of Geographers Annual Meeting, April 7-11.

6. 2020, Spatiotemporal analysis of change in Landsat time series in the eastern Hindu Kush region, 12th BayCEER Workshop at the

University of Bayreuth, Bayreuth, Germany, October 29.

Panel Member

1. 2023, Migration as Adaptation: Assessing Effectiveness and Outcomes (Session 2, B2), ECMN Network Launch and Conference, University of Vienna, July 10-12.
2. 2022, Securing Clean Water in Transboundary Indus, Jordan, Mekong and Amazon Basins Through Science and Environmental Diplomacy (Roundtable), 2nd International Conference on Environmental Peacebuilding, February 1-4.
3. 2022, Highlands to Oceans (H2O): Anticipatory Governance of Hydroclimatic Regime Shifts in the Transboundary Indus, Mekong, Jordan and Amazon River Basins (Roundtable), 2nd International Conference on Environmental Peacebuilding, February 1-4.

Poster Presentation

1. 2022, Khan, S. A., Oikonomou, P. D., & Zia, A. Automated detection of glacier cover changes in the Upper Indus Basin of northern Pakistan. AGU Fall Meeting 2022, Online, Dec 11-15, C44B-04, http://dx.doi.org/10.13140/RG.2.2.29178.57287
2. 2020, Khan, S. A., Sass, O., & Samimi, C. Detecting change in Landsat time series with BFAST in the eastern Hindu Kush region. EGU General Assembly 2020, Online, May 4-8, EGU2020-19630, https://doi.org/10.5194/egusphere-egu2020-19630

B. Declarations

(Eidesstattliche) Versicherungen und Erklärungen

(§ 9 Satz 2 Nr. 3 PromO BayNAT)
Hiermit versichere ich eidesstattlich, dass ich die Arbeit selbstständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe (vgl. Art. 64 Abs. 1 Satz 6 BayHSchG).

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Hiermit erkläre ich, dass ich die Dissertation nicht bereits zur Erlangung eines akademischen Grades eingereicht habe und dass ich nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden habe.

(§ 9 Satz 2 Nr. 4 PromO BayNAT)
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(§ 9 Satz 2 Nr. 7 PromO BayNAT)
Hiermit erkläre ich mein Einverständnis, dass die elektronische Fassung meiner Dissertation unter Wahrung meiner Urheberrechte und des Datenschutzes einer gesonderten Überprüfung unterzogen werden kann.

(§ 9 Satz 2 Nr. 8 PromO BayNAT)
Hiermit erkläre ich mein Einverständnis, dass bei Verdacht wissenschaftlichen Fehlverhaltens Ermittlungen durch universitätsinterne Organe der wissenschaftlichen Selbstkontrolle stattfinden können.

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