



# Climate change impacts on livelihoods in the Eastern Hindu Kush: integrating local perceptions and biophysical data

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## 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 local perceptions of climate change and natural hazards with biophysical data, focusing on the connected impacts in vulnerable mountain regions like the Eastern Hindu Kush. Local livelihoods in these regions depend heavily on the ecosystem services that are sensitive to cryospheric and climatic changes. Addressing a significant gap in the assessment of climate change and natural hazards' impacts on local livelihoods, this study employs an interdisciplinary approach and proposes a framework to link local perceptions with empirical data in Lotkuh Valley of Pakistan. The framework bridges bottom-up methods (household surveys, interviews, and focus groups) with top-down analyses (ERA5-Land climate trends, MODIS snow trends, and Landsat-based Modified Soil Adjusted Vegetation Index [MSAVI] analyzed with Breaks For Additive Season and Trend [BFAST]). 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 proposed framework provides fresh insights by comparative analysis of local perceptions and biophysical data, uncovering areas of convergence (e.g., alignment of flood perceptions with observed changes) and divergence (e.g., misalignment in rainfall variability). Its interdisciplinary approach captures the complexity of mountain vulnerabilities by integrating diverse sources and methods. The findings highlight the compound hazards and their cascading impacts in the area, providing critical insights into the interplay of biophysical and social dimensions of climate change, a nuanced understanding of the impacts of climate change and natural hazards on local livelihoods. The study significantly contributes to the understanding of mountain vulnerabilities in the Eastern Hindu Kush and offers practical implications for policy and adaptation strategies in the region and similar mountain areas.

**Keywords** Climate change · Natural hazards · Climate impacts · Remote sensing · Floods · Pakistan

## Introduction

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). The 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

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in extreme values and the frequencies of temperature-based indices (You et al. 2017; Krishnan et al. 2020). Moreover, the frequency of flooding, both glacial-lake outbursts and run-off floods, has increased in the region (Nie et al. 2021; Molden et al. 2022).

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 natural resource base (Nüsser 2001; Nüsser and Dickoré 2002; Gioli et al. 2019). Changes in weather and climate increase the vulnerability of mountain livelihoods, which is further exacerbated by mountain specificities 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 (Hussain et al. 2016; Vogel et al. 2019; Ajani and van der Geest 2021; Khan et al. 2024). In addition, extreme events triggered by natural hazards pose a serious threat to human lives and often cause displacement (Ajani and van der Geest 2021; Khan et al. 2024). These events also cause the degradation of scarce agricultural land and the destruction of standing crops (Ajani and van der Geest 2021). Moreover, the irrigation network, housing, and infrastructure are also disrupted by these extreme events (Nüsser 2001; Hussain et al. 2016; Ajani and van der Geest 2021). 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; Khan et al. 2024). 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, defined as individuals' understanding of climate-related changes based on their experiences and knowledge, 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; Weber 2016; Poortinga et al. 2019; Sloggy et al. 2021; 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 (Joshi et al. 2013; Banerjee 2015; Hussain et al. 2016; Bhatta et al. 2019; Dilshad et al. 2019; Ajani and van der Geest 2021). These studies reveal that the local populations perceive climate change through noticeable shifts in weather patterns, rising temperatures, and an increase in natural hazards, particularly floods, all of which significantly affect household food security and livelihoods. 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 (Singh et al.; Spies 2020; Dahri et al. 2021). 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 and 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. 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 arid and semi-arid environment (Nüsser and Dickoré 2002), high mountains, and seasonal extremes of precipitation and temperature (Ahmad et al. 2020; Syed et al. 2022). This region is particularly interesting for studying climate change perceptions with hydrometeorological data due to indications of distinct 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 (Ahmad et al. 2020, 2021a). 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, natural extreme events, and their impacts on local 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 impacts of extreme events with the analysis of biophysical data using a conceptual framework (Fig. 2). This framework facilitated the integration by linking data from household surveys, interviews, and focus groups with biophysical analysis, enabling a comparative assessment of convergence and divergence between local perceptions and observed climate and vegetation trends. The framework is further described in the “[Research design and approach](#)” section. 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) selectively show the timing and impact of the flood events detected by remote sensing data compared with survey and interviews.

Our study contributes to climate change research by integrating local perceptions with quantitative data, providing a comprehensive understanding that bridges the gap between community experiences and biophysical data. Focusing on the Eastern Hindu Kush region, characterized by its unique climate trends and a lack of prior research, our work addresses crucial knowledge gaps and adds valuable insights to existing literature. Through an integrated analysis of climate change and an exploration of the region’s susceptibility to multiple hazards, our study enhances the scientific understanding, offering practical implications for

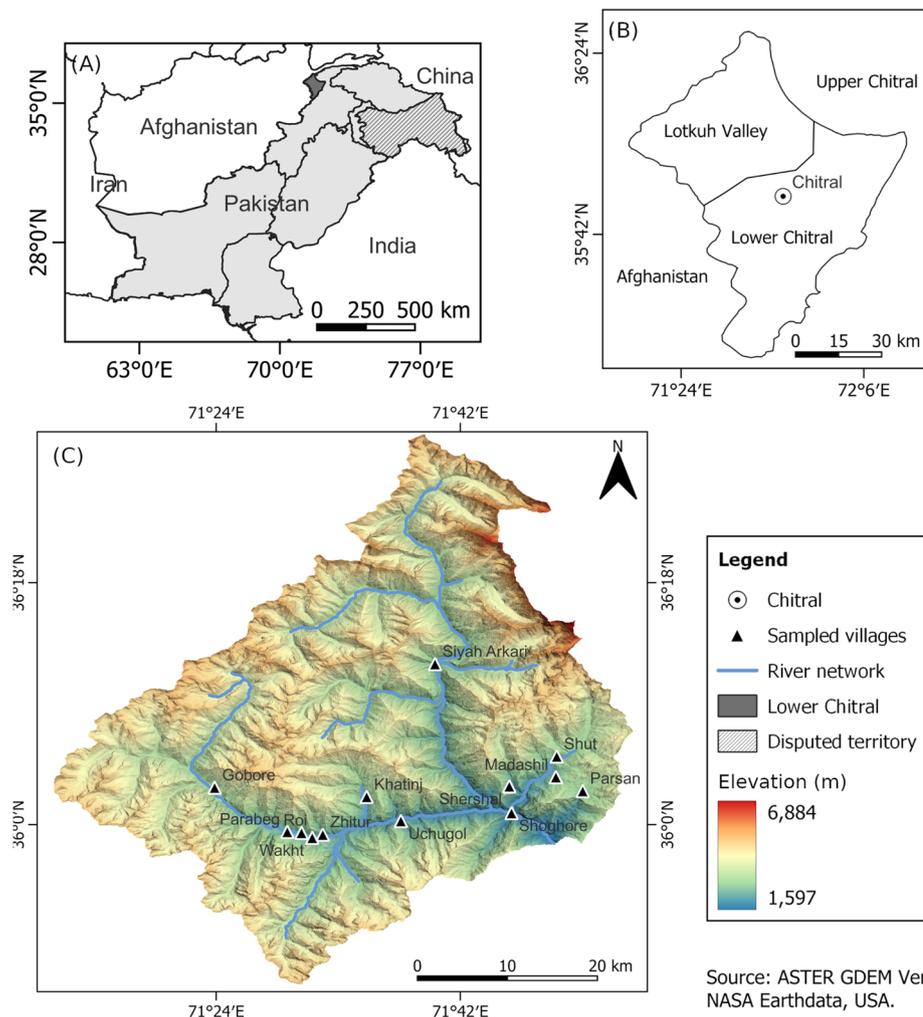
policy development and climate change adaptation in the Eastern Hindu Kush region and similar areas.

## Methods

### Study area

This research was conducted in the Lotkuh Valley located in the Lower Chitral district of Khyber Pakhtunkhwa province of Pakistan (Fig. 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 Garam Chashma with elevation ranging from 1600 to over 6000 m. Geographically, it is situated in the Eastern Hindu Kush region, borders Afghanistan on the west, and is

**Fig. 1** Map of the study area. **A** Lower Chitral in northwest Pakistan, **B** Lotkuh Valley in the Lower Chitral district, and **C** sampled villages in the Lotkuh Valley



Source: ASTER GDEM Version 3 NASA Earthdata, USA.

accessed from Chitral town. The government census in 2017 estimated its population of approximately 45,000 inhabitants and 6600 households.

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 (Ahmad et al. 2021b). 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. The area also receives snow in the winter, and mono-cropping is practiced in some 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, and migration to urban areas (Ahmad et al. 2021b; Khan et al. 2024). Labor, tourism, and out-migration are other sources of livelihood. 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 1). The extreme events adversely affect human lives and livelihoods in the area.

## Research design and approach

This study adopts a mixed-methods research design (Bazeley 2018; Tashakkori et al. 2020; Tashakkori and Teddlie 2021) informed by the sustainable livelihoods framework (Scoones 1998; Natarajan et al. 2022). The framework explains the

**Table 1** Descriptive statistics of the surveyed households in Lotkuh Valley

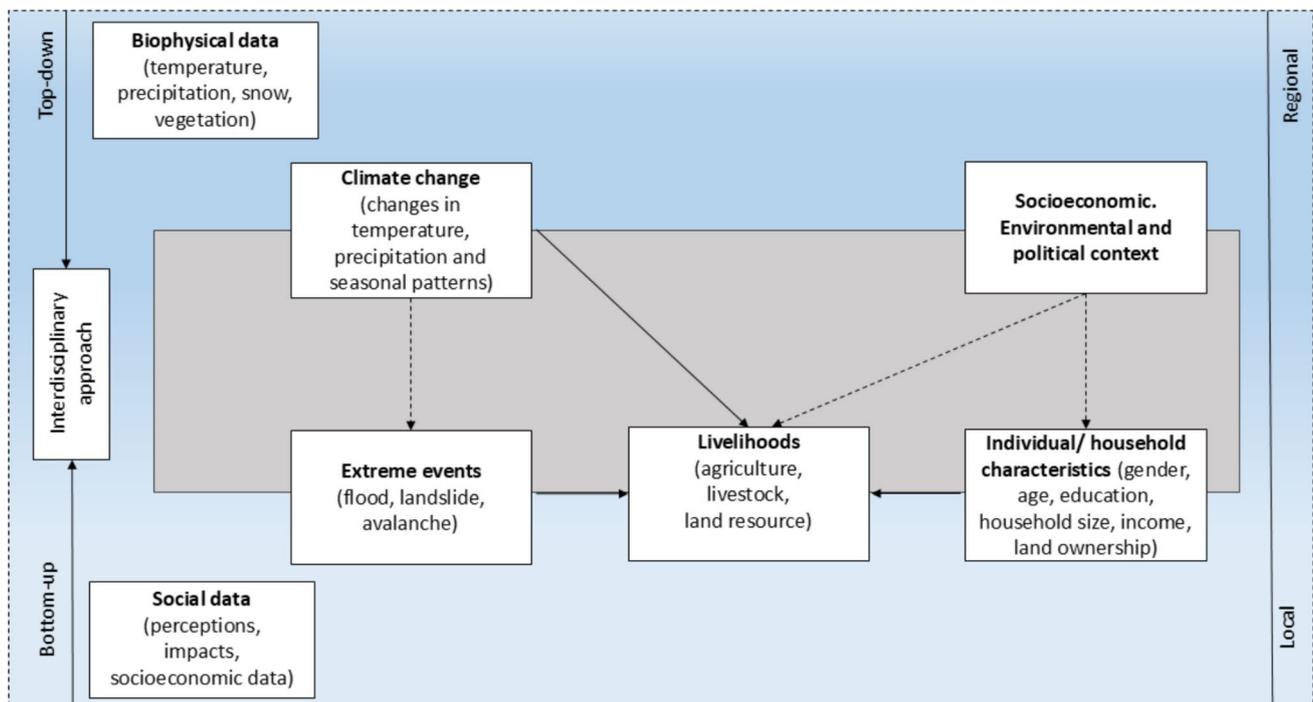
Characteristics	Statistics
Number of respondents ( <i>N</i> )	388
Number of villages	13
Age (Mean: SD)	40.8: 15.4
Gender (F:M)	97:291
Education	
College/university, <i>n</i> (%)	114 (29.4)
Primary–secondary, <i>n</i> (%)	129 (33.2)
Not educated, <i>n</i> (%)	145 (37.4)
Household size (Mean: SD)	7.5: 2.7
Monthly income (Pakistan Rupees)	
> 30,000, <i>n</i> (%)	127 (32.7)
17,500–30,000, <i>n</i> (%)	93 (24.0)
< 17,500, <i>n</i> (%)	168 (43.3)
Ownership of agricultural land, <i>n</i> (%)	342 (88.1)
Affected by an extreme event, <i>n</i> (%)	321 (82.7)

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 maintain or enhance them without undermining the natural resource base of the affected area (Serrat 2017).

In mountain regions, agricultural production, livestock, and land are central to the livelihoods (Gioli et al. 2019). These livelihood strategies are shaped by broader socio-economic and political factors, including access to information, institutional services, and markets, as well as household characteristics such as gender, education, income and landholding (Weber 2016). Lotkuh Valley also experienced such changes in agriculture and livestock practices (Ahmad et al. 2021b, 2023).

To integrate local perceptions with biophysical data, we propose a research framework (Fig. 2) that provides a systematic structure for combining top-down and bottom-up approaches. Furthermore, it also allows to combine both quantitative and qualitative data sources. Quantitative data were collected and analyzed using a household survey, trend analysis of climate data, and time series analysis of remotely sensed vegetation. Qualitative interviews and focus groups were conducted and analyzed to enrich descriptions. 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. The framework draws on the sustainable livelihoods approach (Scoones 1998; Natarajan et al. 2022), as well as on 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 and impacts of climate change.

This framework serves as a guide for the mixed-methods approach employed in this study. It provides a clear and structured process for integrating top-down approaches (climate trends, abrupt changes in land cover) with bottom-up approaches (survey, interviews, focus groups), ensuring coherence in the analysis. The bottom-up analyses are carried out first to develop understanding of perceptions of climate change and experiences of impacts of past hazards. Then, top-down analyses are conducted to find climate trends, and land cover changes. These methods are interlinked by comparing local perceptions of climate change and experiences with extreme events to climate trends and



**Fig. 2** Research framework showing an interdisciplinary approach to integrating perceptions of climate change and its impacts on livelihoods and biophysical data

land cover changes, facilitating a comprehensive understanding of their impacts on livelihoods. This includes examining socioeconomic, environmental, and political context, as well as individual and household characteristics.

### Field data collection and analysis

In the first phase, fieldwork was carried out in the Lotkuh Valley from April to 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 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 (Poortinga et al. 2019; Babanawo et al. 2023). 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 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 described in Kuckartz (2019). Data on perceptions was collected covering the past 20 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). Overall, the selection of survey variables and design of interview and focus groups questions were guided by the framework's focus on linking household characteristics, livelihood strategies, and climate perceptions, ensuring alignment between social data and biophysical analyses.

## 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) (Karl et al. 1999; Peterson et al. 2001; Brown et al. 2010) 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  $< 0\text{ }^{\circ}\text{C}$ ) as a reference for winter duration, summer days (defined as days with maximum temperature  $> 20\text{ }^{\circ}\text{C}$ ) 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. These indices were chosen to complement the study framework's emphasis on integrating biophysical climate data with community-level perceptions and livelihood impacts.

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 (Zandler et al. 2019; Haag et al. 2021). 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 (Zandler et al. 2019; Haag et al. 2021), 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 ERA5 product (Hersbach et al. 2023). The lapse rate describes the temperature change with elevation (e.g.,  $-0.6\text{ }^{\circ}\text{C}$  per 100 m) and is calculated using the temperature at different geopotential heights available from the ERA5 dataset. With this information, the relatively coarse ERA5 product can be adjusted using a higher resolution DEM (JAXA 2023) by deriving the downscaled temperature from respective elevation differences

to the coarser ERA5 product and the lapse rate. 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 ERA5 and Chitral station and found satisfying agreement, with a difference of  $0.002\text{ }^{\circ}\text{C}$  between the station trend and the trend of the corrected reanalysis dataset.

As snow trends can also be derived using optical remote sensing methods, we included an analysis of the daily MODIS Snow Cover product (Hall and Riggs 2021). Missing values were flagged and linearly interpolated using temporally neighboring data, as this approach showed good results in the existing research (Zandler et al. 2020; Haag et al. 2021). 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 and 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 Season and Trend (BFAST) method to demonstrate its impact on the land cover. It was implemented in the R-package BFAST (Verbesselt et al. 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, the application of BFAST, and the post-processing of results are based on the approach illustrated in Khan et al. (2022) in the Eastern Hindu Kush region, and the Ethiopian Highlands (Alemayehu et al. 2023). 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. By validating community-reported flood events with remote sensing data, this method operationalizes the study framework's aim of triangulating local perceptions with biophysical evidence.

## Results

### Perceptions of climate change and its impact on livelihoods

About 98% of surveyed households perceived a change in climate over the past 20 years. Ninety-six percent 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.

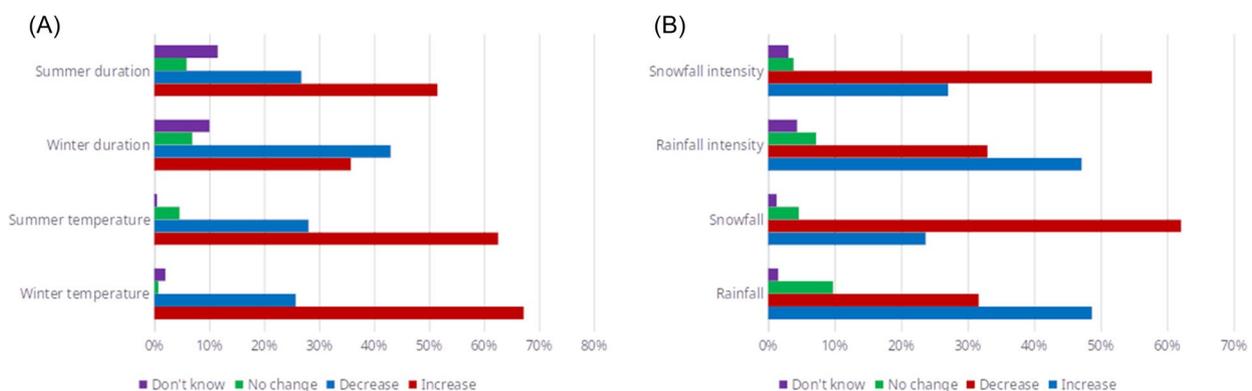
Survey respondents were asked about the manifestations of change in temperature through its impact on length or duration and perceived temperature in summer and winter seasons. The results are shown in Fig. 3A. Most respondents perceived significant changes in temperature and seasonality. A majority reported an increase in both winter (67%) and summer (63%) temperatures. Regarding the duration of the seasons, 52% of respondents perceived an increase in the length of the summer season, while perceptions about the

winter season were more divided. Regarding precipitation, respondents reported mixed perceptions of both rainfall and snowfall changes, as shown in Fig. 3B. A slight majority (49%) observed an increase in rainfall, while 32% perceived a decrease. For snowfall, a majority of 62% of respondents noted a decrease. In terms of precipitation intensity, 47% of respondents observed an increase in rainfall events, whereas a larger proportion (58%) perceived a decrease 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 apricots and apples. 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)

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



**Fig. 3** Manifestations of climate change: **A** changes in temperature and **B** changes in precipitation

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 m 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)

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 that 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 causing a lot of damage to people and houses, so now it is going on. (Interviewee, Shershal)

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)

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)

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)

### 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 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

**Table 2** Influence of socioeconomic and demographic factors on the perceptions of climate change

Variables	Coefficient	Std. error	<i>p</i> -value
Gender (Ref: female)			
Male	2.175	1.292	0.092
Age	− 0.046	0.047	0.332
Education (Ref: college/university)			
No education	− <b>3.536*</b>	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	<b>2.984*</b>	1.465	0.042
Affected by an extreme event	<b>7.266***</b>	2.063	0.000

Significant values are in bold. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

change. Moreover, people who are affected by natural hazards and extreme events are more likely to perceive climate change.

### 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 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 temperature, but a very strong trend in winter for 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 and higher variability in recent years (Fig. 4). Here, only significant linear trend lines are plotted for clarity. 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 3).

**Table 3** Seasonal and annual trends of climate parameters for Lotkuh Valley

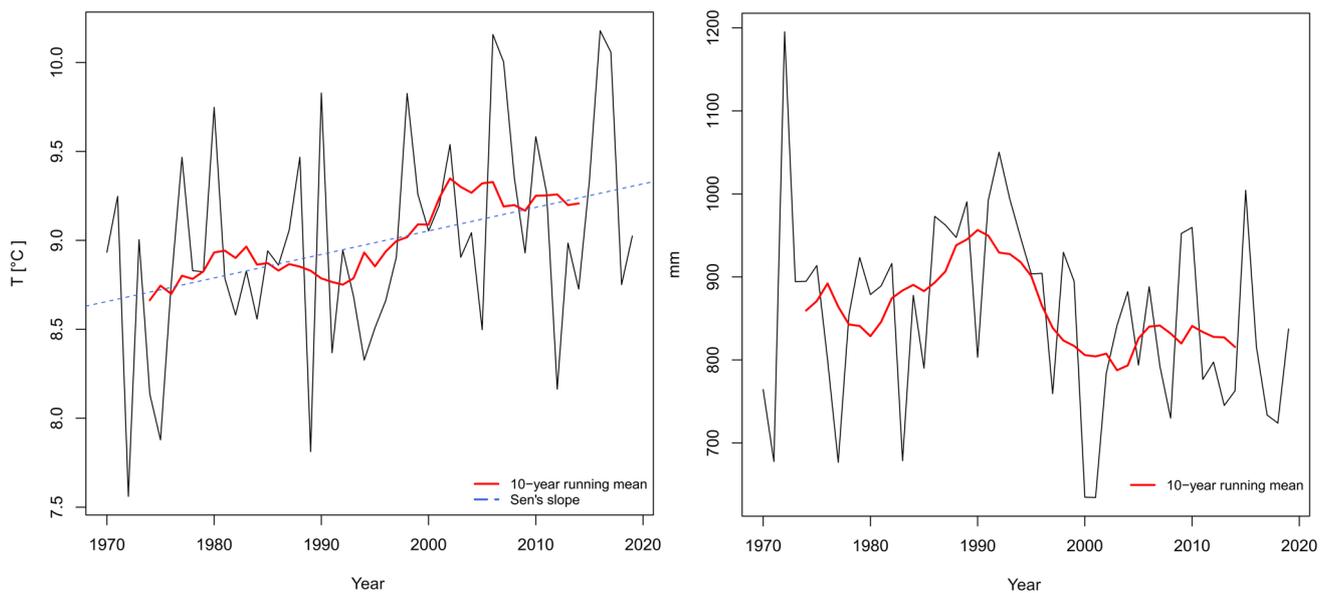
Climate parameters	Prewhitened Sen's slope	<i>p</i> -value
Frost days	− <b>0.241*</b>	<b>0.039</b>
Summer days	0.129	0.361
Summer temperature (mean)	0.006	0.443
Summer temperature (max)	0.013	0.182
Summer temperature (min)	0.002	0.816
Yearly temperature (max)	<b>0.017*</b>	<b>0.013</b>
Yearly temperature (min)	<b>0.012*</b>	<b>0.039</b>
Yearly temperature (mean)	<b>0.014*</b>	<b>0.012</b>
Winter temperature (mean)	0.016	0.274
Winter temperature (max)	<b>0.021*</b>	<b>0.046</b>
Winter temperature (min)	0.011	0.398
Yearly precipitation	− 1.427	0.176
Winter precipitation index	− 0.003	0.797
Summer precipitation index	− 0.003	0.776
Snow cover (mean)	0.057	0.820

Significant values are in bold. \* $p < 0.05$

### 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 (Fig. 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, earthquakes are a quite common geological hazard in the whole Hindu Kush region, which 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 rock-fall in the area.

The spatial analysis of the extreme events is presented in Table 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



**Fig. 4** Yearly average, 10-year running means, and trends of annual mean temperature (left) and precipitation (right)

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 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)

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 Fig. 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)

The survey results showed that the extreme events had impacted the lives and livelihoods of the communities in the Lotkuh Valley (Fig. 7). In terms of loss and injuries to people's lives, avalanches have been deadly (3%) among surveyed households. Moreover, people's homes, which are 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 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 proximity to rivers and streams.

**Table 4** Households (%) affected by natural hazards in surveyed villages ( $n = 388$ )

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	
Parsans	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	

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)

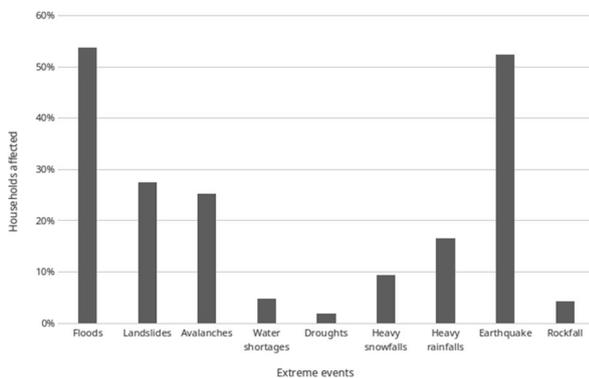
Landslides (18%) and avalanches (18%) also contribute to the loss of agricultural land. Similarly, they also cause land degradation. All these three natural hazards, floods (30%), landslides (12%), and avalanches (9%), severely affect the irrigation channels in the valley. When the households were further asked about the shortages of irrigation water, floods (27%), heavy rainfalls (8%), avalanches (6%), and landslides (5%) were 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)

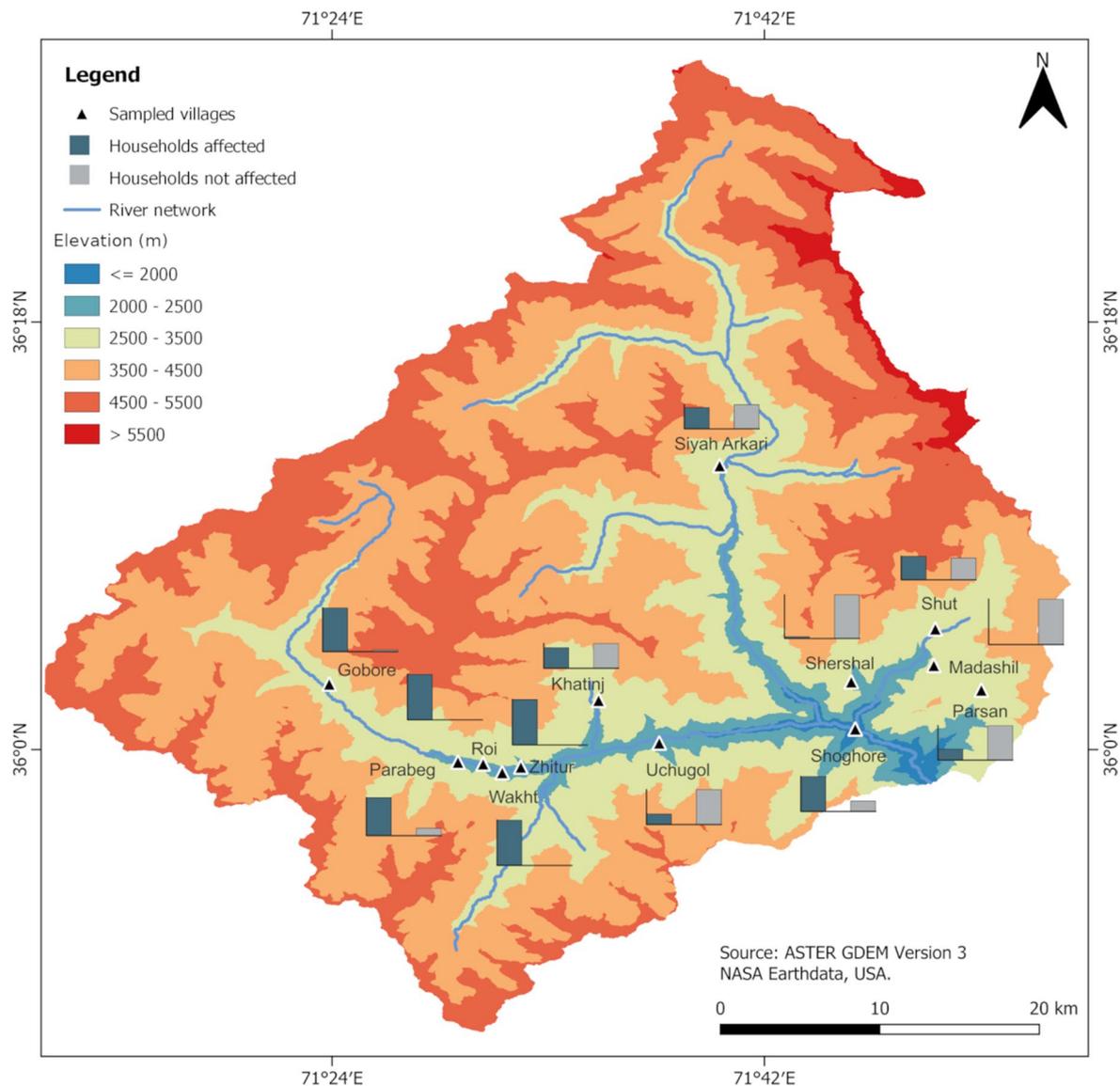
The communities mentioned that the restoration and rehabilitation of the affected irrigation channels is a difficult task that has negative consequences not only for agricultural production but as additional economic and human strain. Crop failure is also reported by the surveyed households mainly caused 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.

**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 (Fig. 8) in Shoghore which were strongly mentioned by local people. Several spells of flooding were detected from February to September 2015, but major 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



**Fig. 5** The proportion of surveyed households affected by various types of natural hazards



**Fig. 6** Distribution of flood impact in the Lotkuh Valley. Percentage of households affected by floods in the sampled villages

phenomenon by the flooding in Shoghore compared to the pre-flood image in which the croplands are flourishing (Fig. 9).

## 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 (Joshi et al. 2013; Hussain et al. 2016), 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 concerning seasonal patterns. On the other hand, people noted a decrease in snow throughout the Lotkuh Valley, which is consistent with perceptions in the Pamirs (Haag et al. 2021) and Booni in Upper Chitral (Ajani and 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

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%

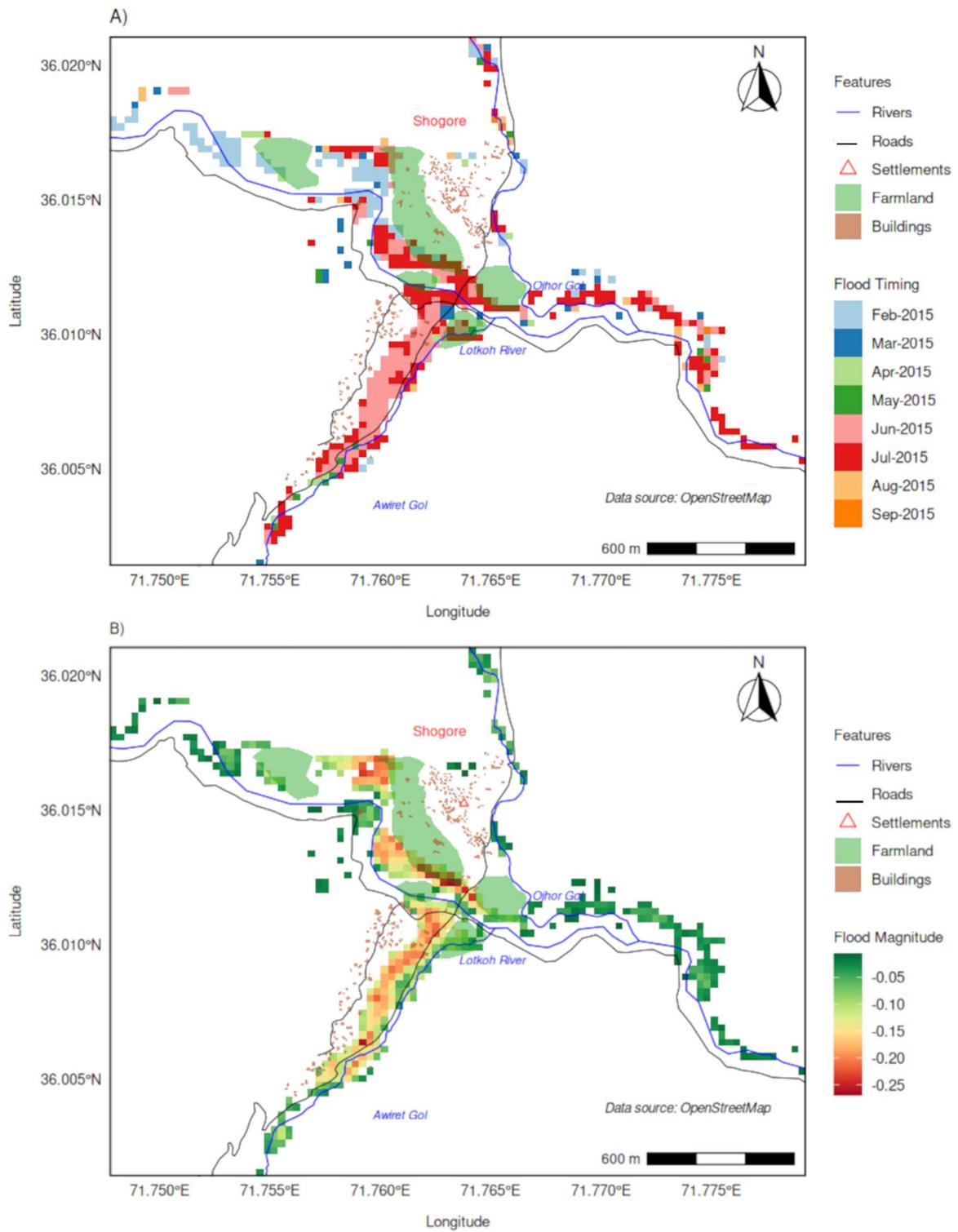
Fig. 7 Impacts of extreme events on the livelihoods of surveyed households (n = 388)

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. For local communities, this shift is significant, as the monsoon rains are often associated with intense rainfall and flooding. This was not traditionally observed in the area and is now increasingly affecting agricultural activities, particularly harvest-ready crops. This new monsoon pattern in the area, as perceived by the local communities, could be linked to subtle localized anomalies rather than long-term trend, given that our data show no significant precipitation trends at the local level. This highlights the need for further exploration into broader local and regional climate patterns. Furthermore, communities would need to adjust to these changes and take proactive measures to minimize localized risks.

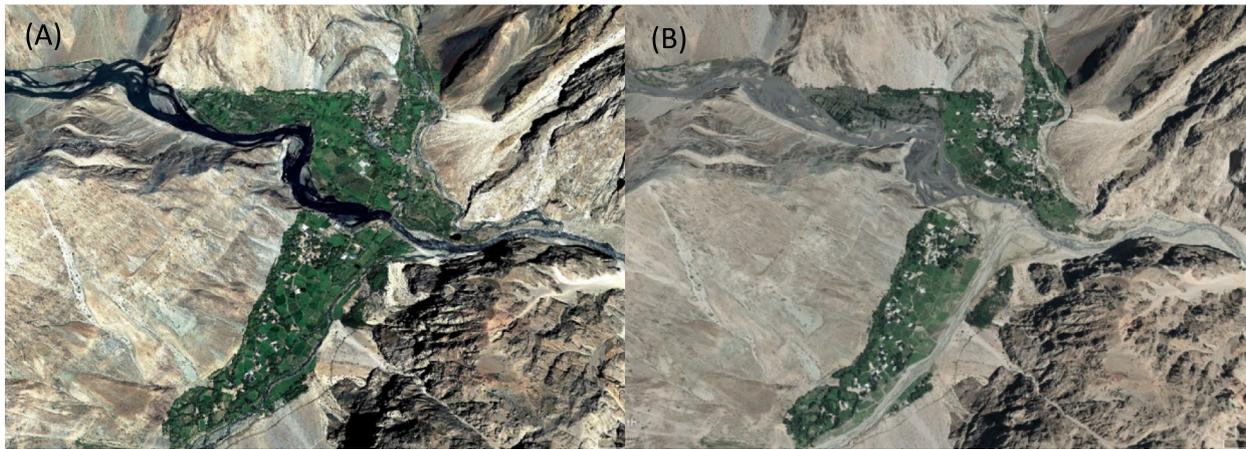
Farmers find rainfall in spring more beneficial as it serves irrigation needs. Overall, the upward trend in temperature and rainfall variability perceived by communities is in line with perceptions reported from other basins in the HKH (Joshi et al. 2013; Dilshad et al. 2019). The perceived increase in annual precipitation and increase in summer rainfall are consistent with perceptions in Hunza and Yasin valleys in the Gilgit-Baltistan region (Gioli et al. 2014).

However, perceptions of increasing rainfall differed from decreasing rainfall noted in the 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 (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 the 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 probably due to the awareness 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).



**Fig. 8** BFAST detected the 2015 flood event in Shogore. **a** The timing of the flooding; **b** the magnitude of change in MSAVI



**Fig. 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 (source: Google Earth)

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 (Ahmad et al. 2021a). Other studies even state the cooling of annual temperatures between 2000 and 2013 (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 (Ahmad et al. 2020, 2021a). Remote sensing data did not reveal any significant trends in snow cover, whereas other regional studies also do not present conclusive trends, as some studies state an increase in snow cover or static conditions or others describe different results from villages near each other (Ahmad et al. 2020, 2021a). 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 that depend on the snow-melt 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 (Bhatta et al. 2019; Ajani and van der Geest 2021).

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 (Hussain et al. 2016; Bhatta et al. 2019; Dilshad et al. 2019; Ajani and van der Geest 2021). Overall, the results (Fig. 7 and Table 4) suggest that multi-hazards in Lotkuh Valley involve a combination of physical damage, loss of livelihoods, and displacement, often triggered by multiple hazards occurring together or one after the other. The interconnected impacts on housing, agriculture, water supply, and human lives underline

the complexity of disaster management and the importance of addressing compound risks through integrated responses.

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 that 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 and 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 and van der Geest 2021; Khan et al. 2024).

Our study framework (Fig. 2) highlights both the convergence and divergence between perceptions and climate trends. 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). Similarly, farmers' experiences with irrigation water shortages, attributed to reduced snow and rainfall variability, have influenced their perceptions (Spies 2020). For example, the erratic summer rains, particularly during monsoon, disrupt the harvest and cause low yield thus also influencing their perception of an increase in rainfall. These insights demonstrate the utility of the framework in capturing the nuances of local perceptions alongside long-term terms, particularly as farmers face increasing difficulty perceiving long-term rainfall changes amid growing variability (Guodaar et al. 2021). However, it is also possible

that the perceived changes in the precipitation patterns are too subtle or localized to be captured by the broader statistical analyses used in this study. For instance, higher rainfall variability in certain months might not be reflected in aggregated seasonal or annual data (e.g., Fig. 4). In this context, farmers' perceptions could serve as a more localized reality of climate change impacts, potentially acting as an early warning signal for changes that are not yet visible in regional weather datasets.

The interdisciplinary framework also demonstrates its value in integrating social and biophysical data. By combining bottom-up approaches (survey, interviews, focus groups) with top-down methods (abrupt change detection in land cover with BFAST, climate trend analysis), it enabled the identification of both synergies and discrepancies between people's experiences and empirical data. For instance, while perceptions suggested significant decrease in snow and increased precipitation, climate trend analysis revealed no significant trends for snow cover or precipitation. The framework's interdisciplinary approach not only highlights areas of alignment, such as flood events, but also uncovers discrepancies, such as rainfall variability, where perceptions diverge from the long-term trends. The divergence underscores the complexity of integrating social and biophysical data and suggests that local perceptions may provide unique and context-specific insights into subtle climate changes that statistical models might overlook. Moreover, the framework operationalizes the sustainable livelihoods approach by linking livelihoods (agriculture, livestock, and land use) with climate variability and broader socioeconomic impacts. This integration facilitated a nuanced spatial analysis, especially in areas where remote sensing validated community-reported flood events, including their timing, extent, and severity. In particular, areas such as Shoghore demonstrated a strong alignment between community perceptions and biophysical data, where the timing and extent of the 2015 flood event matched well with remote sensing results. Our findings suggest that incorporating detailed community narratives and perceptions provides critical insights that might otherwise be overlooked in biophysical analyses, thus offering a comprehensive understanding of multiple hazards and their impacts on local communities.

People's awareness and strong perceptions of climate change in Lotkuh Valley are invaluable for fostering climate change adaptation actions at the local level. These perceptions highlight localized impacts of climate change that might not be captured in broader climate models, and can guide targeted interventions.

Furthermore, the interdisciplinary framework employed in this study highlights how integrating biophysical data with local perceptions can better inform adaptive and risk reduction strategies by identifying areas and sectors most affected by hazards, such as agriculture and infrastructure,

and then tailoring solutions accordingly. For instance, improved flood mitigation measures with community-based trainings on emergency preparedness could reduce the impacts of future floods. This integration is particularly helpful in aligning community-driven adaptation and risk reduction initiatives with national policies, such as Pakistan's National Climate Change Policy and National Disaster Risk Reduction Policy. These perceptions and experiences of local communities enhance their willingness to respond to the challenges associated with climate change and extreme events at the local level (Abid et al. 2019). Furthermore, community awareness encourages mobilization for investing in long-term, sustainable measures to address warming seasons and the connected and compound extreme events that threaten livelihoods (Guodaar et al. 2021). For example, community-led reforestation initiatives could act as barriers to floods while also addressing land degradation problems. By bridging scientific analyses and local knowledge, our results provide a foundation for designing interventions tailored to the unique challenges of the Eastern Hindu Kush. These interventions can include incorporating local insights into district-level planning processes that risk reduction measures align with local community needs and aspirations.

## 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 (abrupt change detection with BFAST, climate trend analysis) to gain holistic and integrated perspectives on climate change in our study area.

The study shows that most people perceived changes in temperature, 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 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.

The interdisciplinary framework employed in this study contributes to the understanding of climate change impacts on mountain livelihoods. By integrating biophysical data, such as abrupt change detection and climate trend analysis, with social science approaches to capture local perceptions, the framework bridges disciplinary gaps and offers a more comprehensive understanding of the climate-livelihoods nexus. This approach allows for the identification of both convergences and discrepancies in observed and perceived climate changes, providing richer insights into how climate change affects local communities.

Our findings showed that most of the villages are prone to multi-hazards. The presence of several hazards causes connecting and compounding 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 research gap in the Eastern Hindu Kush region on climate change and natural hazards' impacts on mountain livelihoods.

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**Author contribution** S.A.K. designed the study, conducted the data collection and analysis, and wrote the manuscript. H.Z. analyzed ERA5-Land and MODIS snow products and reviewed the manuscript. O.S. reviewed the manuscript and supervised the research.

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**Data availability** The datasets generated during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Ethical approval** Approval was obtained from the Research Ethics Committee at the University of Bayreuth.

**Consent to participate** Informed consent was obtained from all the participants in the study. Consent to participate was voluntary and approved by the University of Bayreuth's Research Ethics Committee.

**Competing interests** The authors declare no competing interests.

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