OEconomia
oeconomiajournal.com
Volume: 07, No: 2 (2024)
ISSN: **2269-8450,2113-5207**

Impact of Glacier Mass Balance on Socioeconomic Conditions of the Shigar Valley, Karakoram, Pakistan

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Abstract: Shigar Valley, in the Karakoram Range, relies heavily on glaciers for its water resources, which are vital for agriculture, hydropower, and local livelihoods. However, climate variability is causing significant changes in the glacier mass balance, causing socio-economic impacts. Reduced water availability, increased risk of glacial lake outburst floods, and fluctuations in meltwater flows pose significant challenges for feasibility and stability of hydropower generation. The present study aims to analyze the past and future fluctuations in glacier mass balance in the Shigar Valley and assess its impacts on the socioeconomic conditions of the local communities. We use Open Global Glacier Model (OGGM) to analyze the past dynamics and future trends in mass balance under different climate scenarios by using Coupled Model Intercomparison Project Phase 6 (CMIP6) data. This approach can inform water resource management, disaster preparedness, and economic planning, fostering resilience in Shigar Valley's communities. Our findings reveal mixed trends in glacier mass balance highlighting balance gain in some big glaciers particularly during the 1990s confirming the Karakoram Anomaly, while most of the smaller glaciers have been showing negative mass balance. The findings further reveal that more than 50% of the respondents are highly dependent on glacier meltwater for agriculture and other uses, while majority of the respondents reported that they have been adversely affected by glacier dynamics.

Introduction

Glacier mass balance (GMB) is a crucial indicator of glacier health and ice gain or loss, often reflecting climate change impacts. It provides insights into Earth's cryosphere dynamics. Global trends show a decline in GMB, impacting regional water resources, sea levels, and socio-economic stability. High Mountain Asia's glaciers are vital for freshwater supply, affecting millions of people's socio-economic conditions. They store water in ice and release it during warmer seasons, supporting agriculture, hydropower, and domestic water supply. However, climate change's rapid retreat threatens these resources, disrupting water availability and potentially affecting food security, energy production, and livelihoods (Yadav et al., 2024).

Glaciers in High Mountain Asia, the Himalayas, are retreating at unprecedented rates, with the Nehnar Glacier losing 16% of its area between 2000 and 2020. The Hintereisferner Glacier in the Alps experienced significant mass loss during 2021/2022. The Urumqi Glacier No. 1 in China experienced a dramatic decline in mass balance over 41 years, reflecting the broader regional impacts of climate warming. This consistent global decline in glacier mass balance is evident in many regions, despite some localized exceptions (Dixit et al., 2024).

The dynamics of glacier mass loss are complex and multifaceted, involving processes like ice flow acceleration, calving, and underwater melting. Understanding these dynamics is crucial for predicting future glacier behavior and their contribution to sea level rise. Advanced monitoring and modeling techniques are needed to accurately capture these dynamics and their implications for global climate systems. However, challenges remain, such as discrepancies in mass change estimates due to variations in measurement methodologies and interpretations, underestimation of glacier volume, and difficulties in accurately calculating mass change. Addressing these challenges is essential for refining projections of future sea-level rise and informing global efforts to mitigate and adapt to climate change (Hassan, et al., 2024; Liu et al., 2024).

The Karakoram Anomaly, a glacier stability issue in the Himalayan Mountain chain, is attributed to the unique climatic characteristics of the Karakoram Range, including higher snowfall in winter and lower summer temperatures. The high altitude, rocky landscape, steep topography, and extensive debris cover contribute to glacier stability, and satellite photography and remote sensing investigations confirm its persistence (Halvorson , 2024; Mandal et al., 2024).

The Open Global Glacier Model (OGGM) is a useful tool for studying the behavior of glaciers in the Karakoram Range, including the Shigar Glacier Anomaly (Pesci et al., 2023). It reproduces the glacier's mass balance, ice movement, and geometric changes, allowing researchers to investigate climatic and topographic elements. The model also simulates the effects of increased winter snowfall and lower summer temperatures and helps understand surface insulation's contribution to glacier stability and give the future prediction on the base of different scenario (Bhat et al., 2024).

The shrinking glacier mass balance poses a socio-economic challenge, potentially causing water scarcity during critical agricultural seasons, impacting food production and vulnerability in rural communities. Increased likelihood of glacial lake outburst floods also poses risks to infrastructure and human lives. Changes in glacial meltwater levels could lead to crop failures, reduced productivity, and food security threats in regions already facing water scarcity and population pressures. Additionally, disruptions in the energy sector, relying on consistent river flow, could reduce energy output and impact urban and rural populations (Agarwal et al., 2023). The Shigar Valley's glacier mass balance (GMB) is undergoing significant changes due to climate change, posing significant challenges to the region's socio-economic stability. The valley's reliance on glacial meltwater for agriculture, hydropower, and essential services is becoming increasingly precarious. Negative trends in GMB, where glaciers lose more mass than gain, are threatening water availability, agricultural productivity, food security, and local communities' economic well-being. The risk of glacial lake outburst floods is also posing severe hazards to infrastructure, property, and human lives. Addressing these challenges is crucial for the sustainable development and resilience of Shigar Valley.

Study Area

Shigar Valley, situated in northern Pakistan's Gilgit-Baltistan region, glaciated landscapes of the Karakoram Range. It extends from the convergence of the Indus and Shigar Rivers and includes K2 peaks. Shigar Valley in northern Pakistan features rugged mountainous terrain, steep valleys, and expansive glaciers. Its elevation ranges from 2,000 to 4,500 meters (Figure 1). The Shigar River provides vital water resources. The Shigar Valley in Pakistan has a high-altitude climate with cold winters and mild summers, influenced by its elevation and surrounding peaks and receives less than 200 millimeters of annual rainfall, primarily snowfall. This snowfall is crucial for the region's water resources, which are essential for agriculture. The population of valley is 30,000 to 40,000, primarily ethnic Balti people. Most live in small communities, with Shigar as the administrative and commercial center (Afreen et al., 2024).

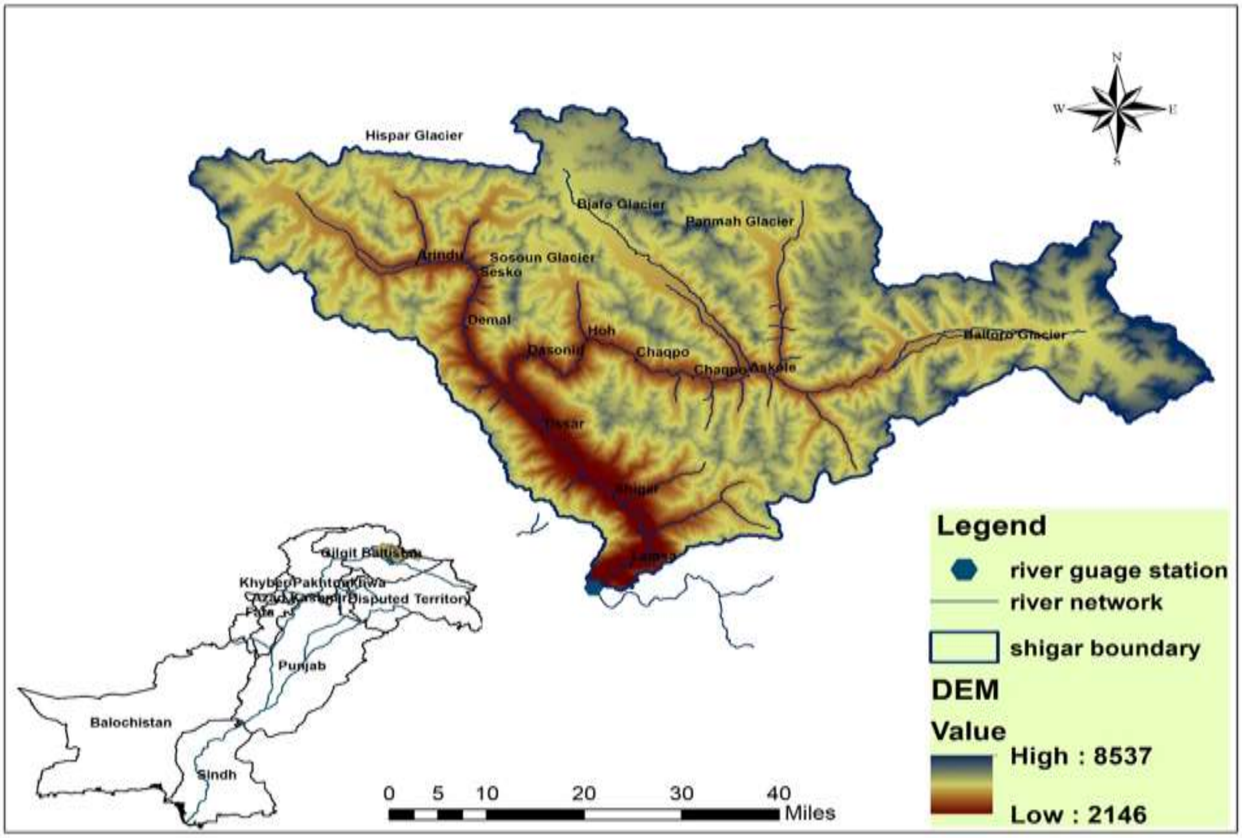


Figure 1: Location Map of Shigar Valley, Gilgit-Baltistan, Pakistan

Methods and Material

To understand the impact of glacier melting on agriculture, a multidisciplinary research strategy is employed, involving various scientific disciplines such as glaciology, hydrology, remote sensing, and socioeconomic analysis. The methodology uses field survey, advanced modeling technique (OGGM), and socioeconomic evaluations to study the intricate relationships between climate change, glacier dynamics, and agricultural sustainability in the Shigar Valley.

Data For Glacier Mass Balance

The Open Global Glacier Model (OGGM) is a powerful tool for analyzing glacier dynamics and mass balance globally. To use it, the data must be preprocessed to meet OGGM criteria, including reprojecting, clipping, and filling gaps. The generated DEM is then integrated into OGGM, acting as the foundation for future modeling operations, ensuring accurate flowline estimates.

Digital Elevation Model (DEM)

The Digital Elevation Model is essential for delineating glacier boundaries and simulating glacier dynamics (Silwal et al., 2023). To achieve accurate modeling, high-resolution DEM data for the Shigar Valley glaciers were acquired from Global Digital Elevation Model (GDEM). These DEM data of Shigar Valley glacier were then meticulously preprocessed to align with the requirements of the Open Global Glacier Model (OGGM), ensuring compatibility for initializing the glacier directory.

Glacier Outlines Data

Glacier outlines are crucial for model initialization and realistic simulation (Reinthaler & Paul, 2024). Therefore, the Shigar Valley's glacier outlines were downloaded from Global Land Ice Measurements from Space (GLIMS) and Randolph Glacier Inventory.

Historical Climatic Data

Historical climate data for glacier dynamics were explored from Climate Research Unit (CRU) and the European Centre for Medium-Range Weather Forecasts' ERA5 reanalysis dataset.

Setup of Open Global Glacial Model (OGGM)

The Open Global Glacier Model (OGGM) is an open-source system used in glaciology to study glacier dynamics, mass balance, and climate change response. It models glacier flow, snow and ice accumulation, and interaction with the environment using climatology concepts. OGGM provides insights into past, present, and projected changes in glacier systems (Amschwand et al., 2024). The OGGM's glacial mass balance module uses an upgraded version of Marzeion's temperature index model. Equation (1) was used to predict the monthly glacier mass balance **(Mi)** at height **z**.

$$\mathbf{Mi(z) = P_i^{solid}(z) - d_f \cdot \max(T_i(z) - t_{melt}, 0)} \tag{1}$$

The study uses a temperature index model to accurately describe glacier mass balance. The model uses P_{solid}, Ti(z), and tmelt to measure solid precipitation. The temperature is classified as 100% solid when it is equal to or below the solid temperature threshold (T_{solid}) of 0°C, and 0% when it is equal to or above the liquid temperature threshold (T_{liquid}) of 2°C. Linear interpolation is used to calculate the percentage of solid precipitation at temperatures between T_{solid} and T_{liquid}. Glaciers have a degree-day factor (df) of kg m−2 K−1 month−1. The proportion of solid precipitation fluctuates linearly dynamic (Khadka et al., 2023). Three main factors are used to describe different temperature index model versions: the degree-day factor (melt_f), the precipitation scaling factor (pf), and the temperature bias (temp_bias). These parameters are crucial in downscaling local climatic data and removing biases, ensuring the model's accuracy in recreating glacial dynamics (Mitra et al., 2022).

The Open Global Glacier Model (OGGM) is a powerful tool for studying the unique behavior of glaciers in the Karakoram Range, including the Shigar Glacier Anomaly. Its extensive capabilities allow researchers to explore the glacier's mass balance, ice movement, and geometric changes, enabling them to investigate climatic and topographic elements contributing to its unique behavior. OGGM can simulate the effects of increased winter snowfall and lower summer temperatures, as well as debris cover effects, which help understand the glacier's stability. This tool is useful for understanding the complex dynamics of the Shigar Glacier Anomaly and forecasting its future behavior under different climate scenarios.

Field Survey

Data were collected through quantitative methods, including water flow rates and quality evaluations. Qualitative data were collected through interviews and focus group discussions with local farmers and community leaders. A total of 375 questionnaires were filled out by respondents from 11 different villages in the Shigar Valley. the questionnaire included both open and close ended question with a comprehensive coverage of sociocultural and environmental perceptions of the local communities. Field observations were also used to document irrigation equipment status, cropping patterns, and any changes in agricultural practices due to variations in water supply. The study used SPSS software and Excel for data analysis and visualization of the socioeconomic impact of glacier melting on agriculture. SPSS was used for descriptive statistics, inferential statistics, and factor analysis to investigate the links between glacier melting intensity and agricultural outcomes.

Results and Discussions

Mass Balance Dynamics

The Baltoro Glacier's glacier mass balance from 1980 to 2020 demonstrates significant changes. The glacier fluctuated between positive and negative values, with significant peaks in 1995 and 1998 and periods of mass loss in the early 2000s and 2010. From Figure 2 the dotted trend line shows a slightly positive trend over 40 years, indicating insistence and rare increase rather than a gradual decline. The Biafo Glacier's glacial mass balance from 1980 to 2020 shows yearly fluctuations, consistent with the Karakoram anomaly. The glacier's mass balance varies significantly for 40 years, with peaks and troughs indicating significant mass increase and loss. Notable positive peaks occurred in 1995, 1998, and 2016, while significant losses occurred in 1980, 2001, and 2010. From Figure 2 the dotted trend line shows a slightly positive overall trend.

The Sosoun Glacier's mass balance from 1980 to 2020 varies significantly, indicating periods of gain and loss. The graph shows peaks and troughs, with significant gains in 1996, 1998, and 2016, and significant decreases in 1980, 2001, and 2010. From Figure 2 the dotted trend line indicates a slight upward trend. The Panmah Glacier's mass balance data from 1980 to 2010 reveals significant variations in mass gain and loss over 40 years. Early years showed negative numbers, while later years showed positive numbers. From 1998 to 2014, the data showed a mix of positive and negative numbers, with notable gains in 2007, 2011, and 2016. From Figure 2 The overall trend line is expected to show a little positive or steady trend, consistent with the Karakoram anomaly.

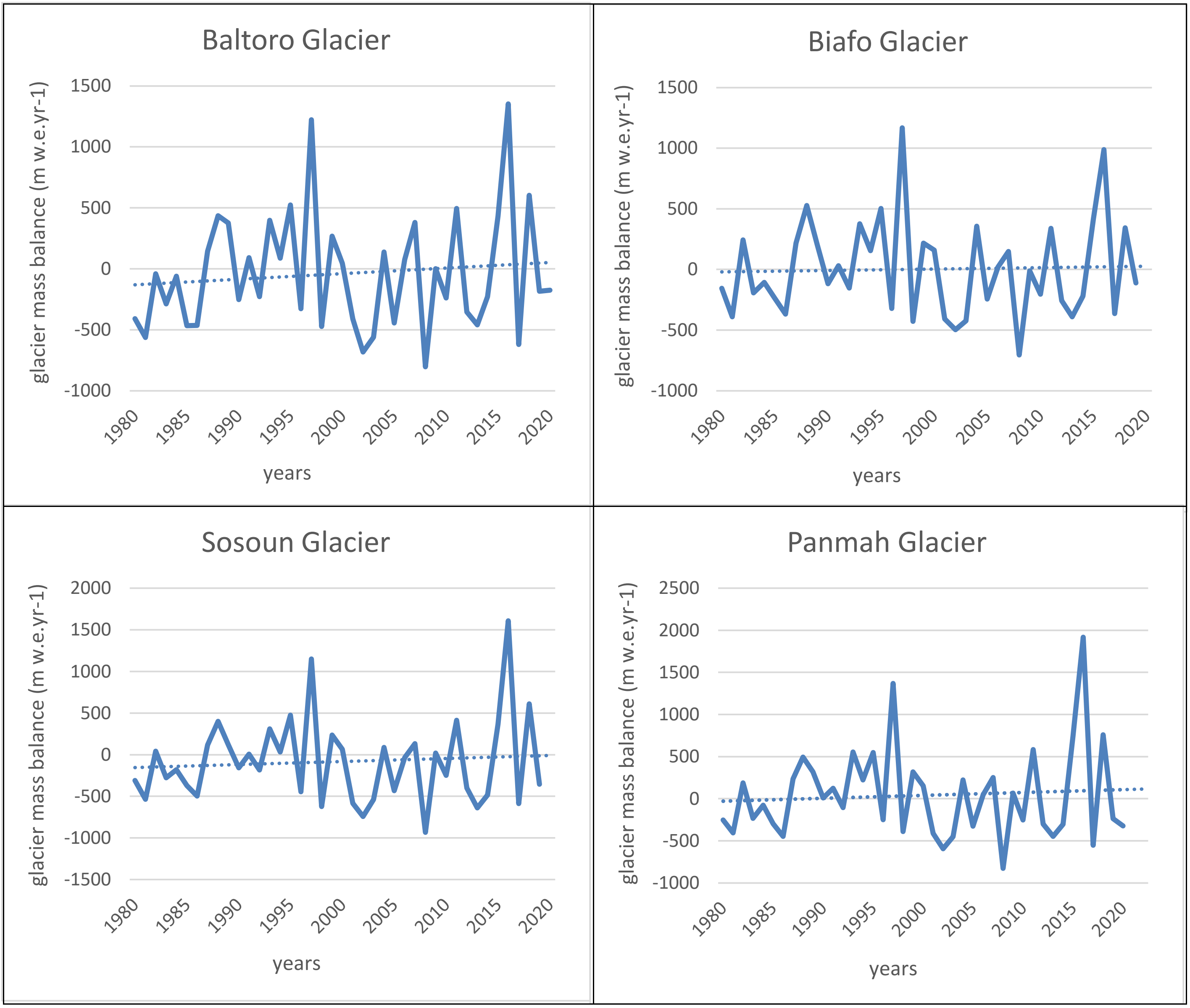


Figure 2: Mass balance of Baltoro, Biafo, Sosoun and Panmah glacier from 1980 to 2020.

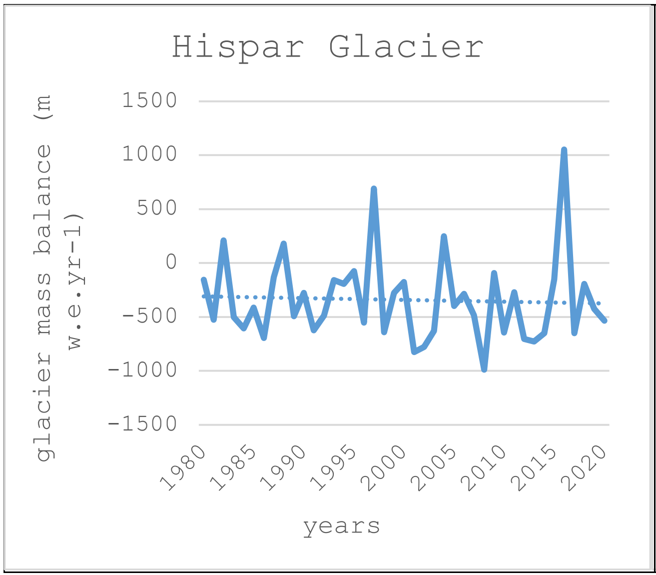
The Hispar Glacier's mass balance statistics from 1980 to 2020 show high variability, with significant variations between years of mass gain and loss. The glacier experienced significant losses in the early 1980s, but a temporary reprieve in 1982. Variability persisted into the late 1980s and early 1990s, with significant changes. From 2005 to 2014, mass balances were consistently negative, with 2016 being one of the highest recorded years shows in Figure 3. The trend of fluctuation in general suggests that net mass loss will occur throughout this time span.

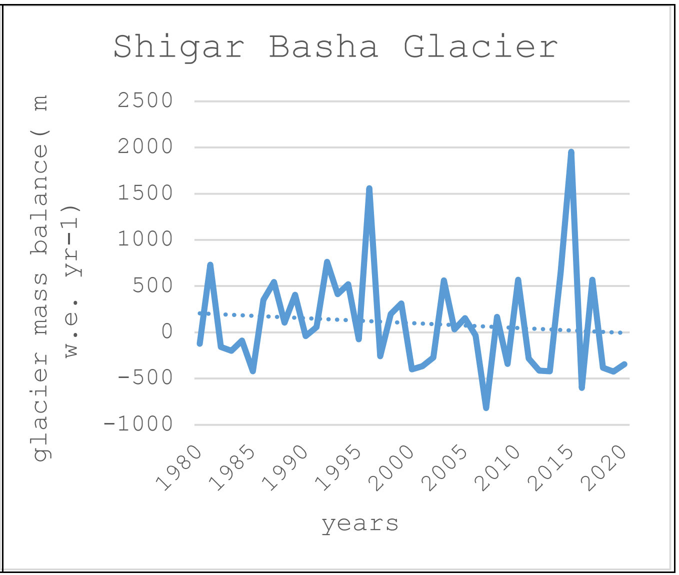
The Shigar Basha Glacier's mass balance graph from 1980 to 2020 shows significant oscillations over a 40-year period. Initial negative balances indicate major ice loss, while 1981 shows significant ice growth. The glacier experienced alternating gains and losses between 1985 and 1990, with 1992 being a significant gain.

The early 2000s saw primarily negative balances, with 2007 being particularly intense. The most recent decade (2010-2020) saw frequent and severe negative balances, with major losses in 2011, 2012, 2013, 2016, and 2017 shows in Figure 3. The graph suggests constant glacial mass loss, possibly due to larger climate changes.

The Chogo Glacier's mass balance graph from 1980 to 2020 reveals significant swings, with periods of both positive and negative balances. The glacier's fluctuation reflects its susceptibility to climatic and environmental changes over the past four decades. The early 1980s saw varied mass balance values, with positive spikes in 1981 and 1986. The late 1980s and early 1990s were stable, but the mid-1990s saw significant fluctuations, with a peak in 1996 and a sharp decrease in 1997. The 2000s saw increased variability, with a significant rise in 2014 and 2015 but a fall in 2016 and 2017 (Figure 2). Overall trends show the decline in Chogo glacier.

The Shingchupki Glacier's mass balance from 1980 to 2020 shows significant interannual fluctuation, with periods of positive and negative balances. The overall trend is decreasing, indicating a net loss of glacial mass. The early 1980s saw predominantly negative balances, while the mid-1980s saw alternating positive and negative balances. The early 1990s showed a moderate downward trend, with a large positive balance in the mid-1990s. The 2000s saw a typical negative trend, with significant negative balances in 2007 and 2012 (Figure 3). Overall trends show that negative mass balance and decrease in glacier.





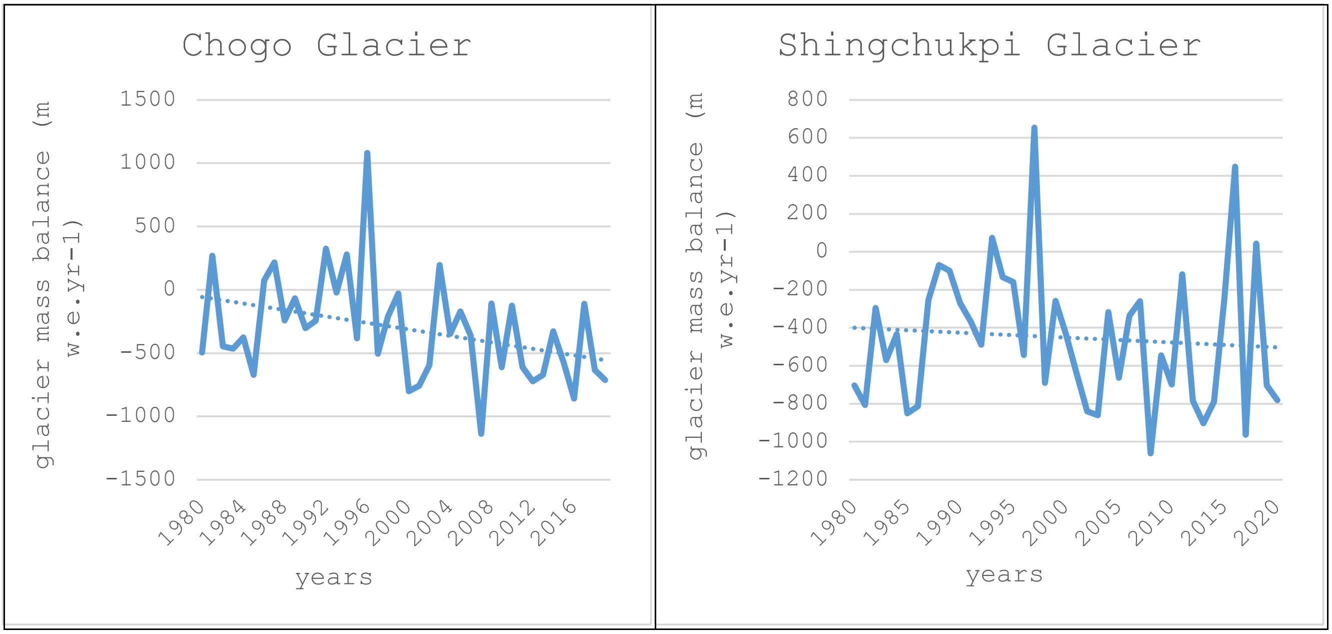


Figure 3. Mass balance of Hispar, shigar basha, Chogo and Shingchupki glacier.

Scenario based futuristic glacier mass balance

The (ssp126) graph shows Figure 4 a volatile trend over 80 years, indicating a long-term decline in glacial mass. However, this reduction is not consistent and has significant year-to-year variability. The graph shows fast short-term fluctuations, with deep troughs around 2025, 2050, and 2080 indicating significant loss. There are periodic dramatic upward surges, but these are short-lived and followed by sharp falls. The graph highlights the complexities of glacier dynamics under changing climate conditions, with a general downward trend from 2020 to 2100.

The graph 'Annual Mass Balance of Selected Glaciers (ssp370)' shows Figure 4 a negative mass balance for selected glaciers from 2020 to 2100, indicating mass loss over time. The rate of mass loss varies but remains below zero, indicating glaciers are melting faster than acquiring mass through precipitation and other causes. This pattern highlights glacier retreat caused by climate change, impacting sea levels and water resources, and highlighting the critical issue of climate change.

The (ssp580) graph Figure 4 reveals a steady loss of glacial mass over 80 years, with significant variations in mass balance. The early period (2020-2040) has the least negative mass balances, while the middle phase (2040-2070) shows growing variability and a shift towards greater negative balances. The graph also shows steep drops between 2060 and 2090, indicating climate change-related glacier retreat.

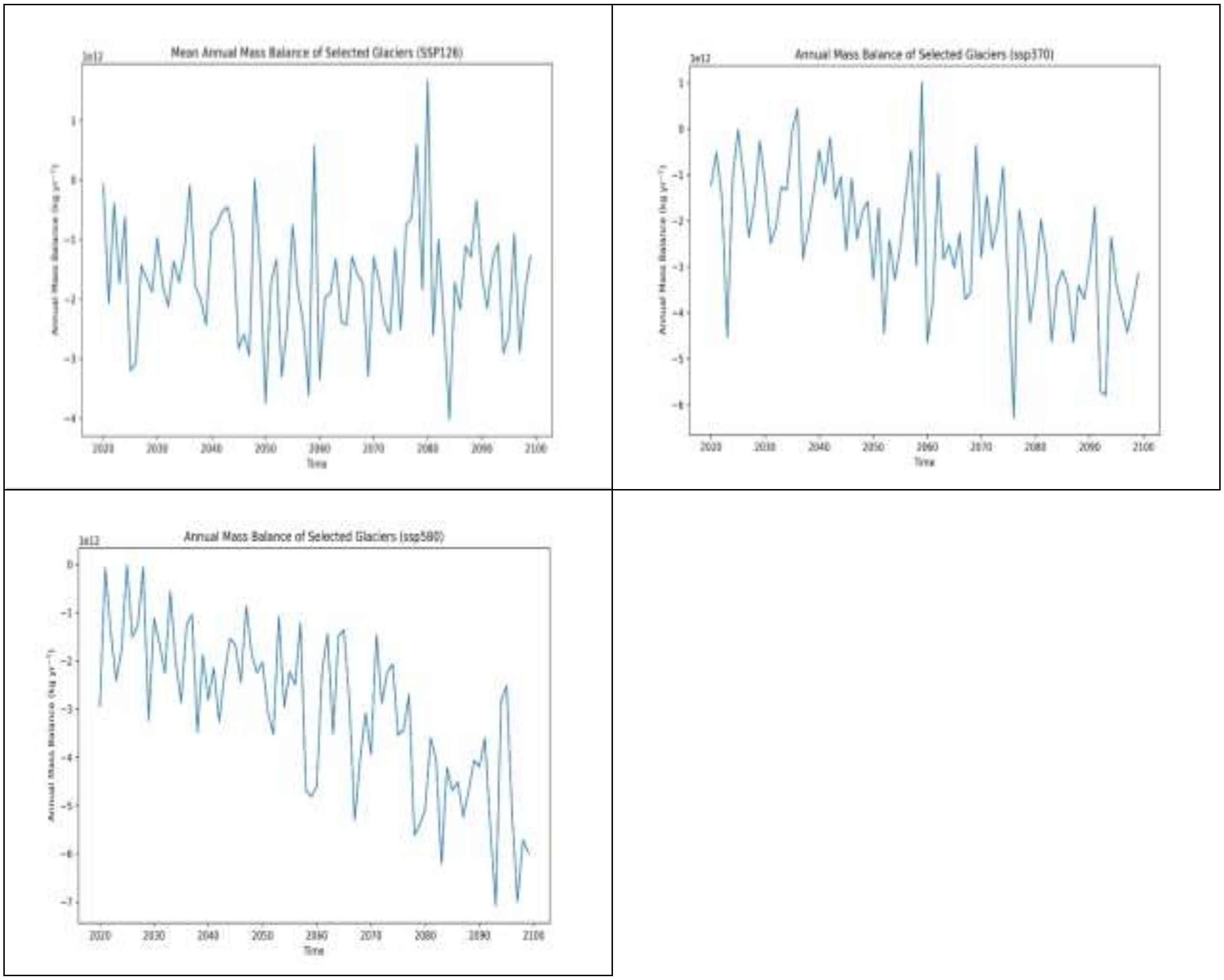


Figure 4 Futuristic prediction (ssp126), (ssp370), (ssp580) scenario of climate using OGGM.

Interplay between glacier dynamics and socioeconomic conditions of communities

The Shigar Valley in Gilgit-Baltistan, Pakistan, relies heavily on glacier melt and snowmelt runoff for water, crucial for agriculture and home usage. This field investigation aims to understand how climate change affects glacial mass balance and agricultural output, assessing seasonal and annual water availability, crop yields, land distribution, and farmer adaptation strategies. A comprehensive survey of 375 respondents, including landowners and farmers, was conducted to gather data on land ownership, water usage, and agricultural practices. The results aim to improve policy and decision-making processes for better resource management and climate adaptation measures, helping local people build resilience to climate change and ensure the long-term viability of their agricultural techniques.

The Shigar Valley's annual household income data shows a skewed distribution, with a large share of households earning lower salaries and fewer households in higher income levels. This suggests potential socioeconomic differences in the region, which could be influenced by factors such as glacial mass balance and snowmelt runoff. Most respondents (216) make less than 20% of their overall income from animal husbandry, which is a supplementary rather than primary source. Animal husbandry is part of many Shigar Valley residents' income portfolios, but it is mostly a supplemental source. The distribution of agricultural income also provides crucial insights, with 128 people generating 20-40% of their total income from agricultural activity. Another large category consists of 100 respondents who make less than 20% of their income from agriculture, indicating that agriculture is a supplementary rather than primary source of income (Figure 5). The varied degrees to which agriculture contributes to the overall income of the Shigar Valley people are also evident.

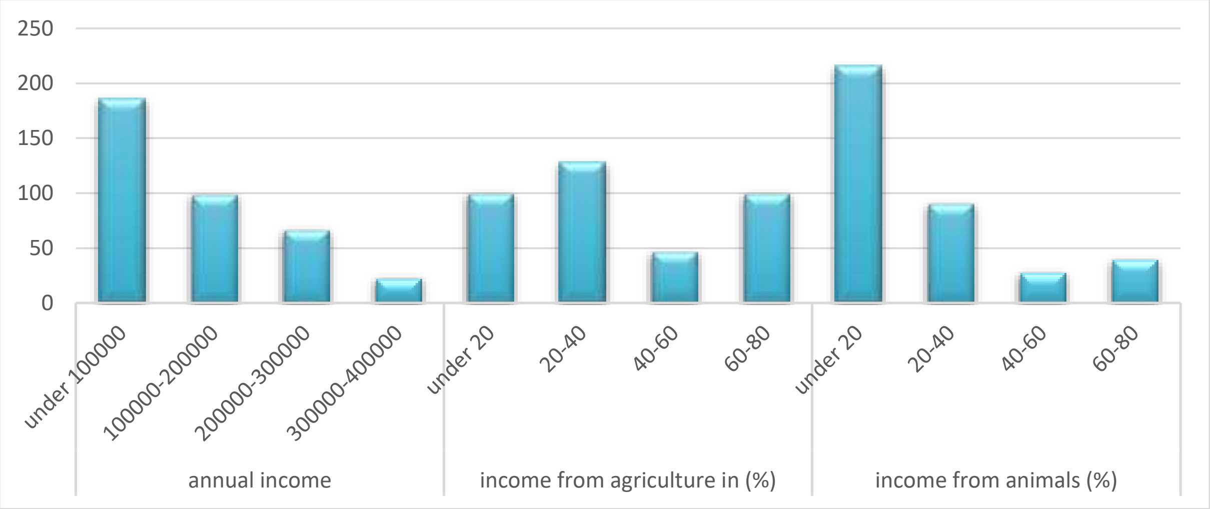


Figure 5. Annual household income and contribution of different sectors

The Shigar Valley is subject to a multitude of natural hazards, with a significant portion of the local population reporting direct impacts from these events. Specifically, 28% of respondents indicated that they have been affected by multiple glacial and hydrological hazards, while an equal percentage reported frequent exposure to flooding (Figure 6). These findings align with the results of a recent study conducted by our team, which employed a multicriteria hazard susceptibility assessment to evaluate the vulnerability of the Shigar Valley (Afreen et al., 2024). The study revealed that the valley is particularly susceptible to a range of natural hazards, driven by a complex interplay of environmental and climatic factors (Hewitt, 2013; Ives, 2012). One of the primary contributors to this heightened vulnerability is the dynamic nature of glacier mass balance within the region. The fluctuations in glacier mass balance—characterized by periods of both significant ice loss and gain—are closely linked to the occurrence and severity of glacial and hydrological hazards. As the glacier mass balance becomes increasingly negative due to climate change, the resultant accelerated melting of glaciers leads to an excess of meltwater, which contributes to the formation of glacial lakes and increases the risk of glacial lake outburst floods (GLOFs) (Kääb et al., 2015; Richardson & Reynolds, 2000). These GLOFs, in turn, have the potential to trigger catastrophic downstream flooding, which can devastate communities, infrastructure, and agricultural lands (Bajracharya et al., 2007).

In addition to GLOFs, the variability in glacier mass balance also influences the frequency and intensity of other hydrological hazards, such as riverine floods and landslides. During periods of intense glacier melt, the sudden influx of water into the valley's river systems can overwhelm existing drainage capacities, leading to widespread flooding. This is further compounded by the steep topography and unstable geological conditions of the region, which are prone to landslides (Gardelle et al., 2013). The combination of these factors creates a scenario in which the valley's communities are exposed to multiple, overlapping hazards, each with the potential to exacerbate the impacts of the others (Fowler & Archer, 2006). Furthermore, the sensitivity of the Shigar Valley's ecosystem to climate variability means that even small changes in temperature or precipitation patterns can have outsized effects on glacier dynamics and, consequently, on hazard occurrence. The region's glaciers, many of which are heavily debris-covered, are particularly sensitive to shifts in the thermal regime, which can alter the rate of melt and influence the stability of ice masses (Bolch et al., 2012). These changes in glacier behavior not only increase the likelihood of hazard events but also complicate efforts to predict and mitigate their impacts (Pritchard, 2019).

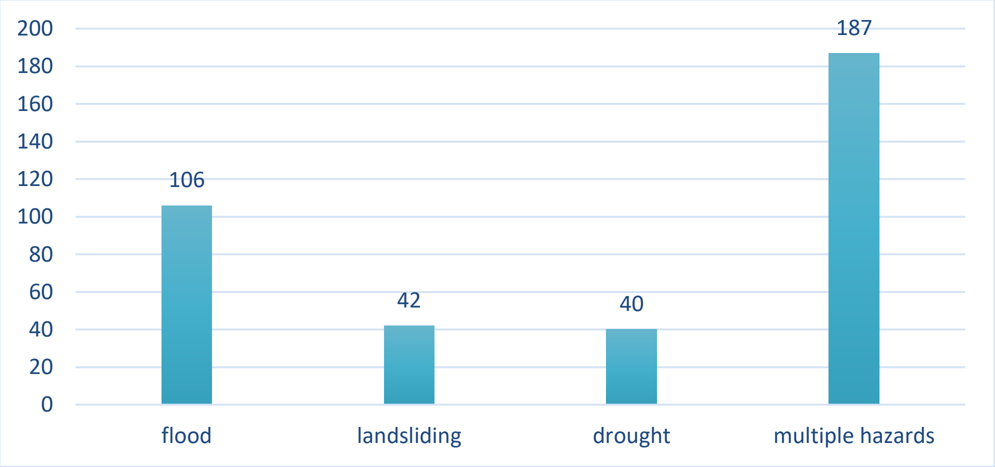


Figure 6. Perceptions of local community about exposure to various hazards

The communities residing in the floodplain regions of the Shigar Valley, directly influenced by the presence and behavior of glaciers, have increasingly transformed the proglacial zones and narrow corridors along the streams into centers of economic activity. These areas, once dominated by natural landscapes, are now being developed for a variety of purposes, creating both opportunities and challenges for the local population (Hewitt, 2014; Kääb et al., 2015). On the one hand, this transformation has facilitated the emergence of new economic opportunities for residents. Agricultural activities, which are the backbone of the valley's economy, have expanded into these newly utilized lands. The fertile soils of the floodplains, enriched by glacial sediments, are particularly conducive to the cultivation of various crops, including high-value fruits (Khan et al., 2020). This has led to the diversification of agricultural outputs, contributing to food security and providing a source of income for many families (Gardelle et al., 2012). Additionally, animal husbandry has thrived in these areas, with the abundant pastures offering ideal conditions for livestock rearing. The development of infrastructure, including roads, irrigation systems, and residential settlements, has further supported these activities, while the burgeoning tourism sector, attracted by the valley's stunning glacial landscapes, has created additional revenue streams (Bolch et al., 2012; Rasul et al., 2011).

However, the intensification of economic activities in these sensitive areas has also heightened the risks associated with natural hazards. The construction of infrastructure and the expansion of agricultural lands into proglacial zones have altered the natural flow of water and increased the vulnerability of these areas to flooding and other glacial-related hazards (Richardson & Reynolds, 2000). The narrowing of natural waterways due to human encroachment exacerbates the risk of flooding, particularly during periods of intense glacier melt or heavy rainfall. The establishment of settlements in these areas also means that more people and property are at risk from glacial lake outburst floods (GLOFs) and other extreme events (Harrison et al., 2018). Moreover, the increased demand for water to support agricultural and other economic activities has intensified the dependency of the local population on glacial meltwater.

Our research findings underscore this dependency, revealing that a significant majority of the population—68% of respondents—report a high to very high reliance on glacier meltwater for their agricultural activities. This dependency is particularly concerning in the context of climate change, as the stability and availability of glacial meltwater are increasingly uncertain (Immerzeel et al., 2020). The reliance on glacial meltwater is further complicated by the recognition of other water sources and variables that contribute to the overall water supply in the valley. While 26% of respondents acknowledge the role of these alternative sources, they remain secondary to the critical input provided by glacial meltwater (Bajracharya et al., 2015).

Snowmelt, another key component of the valley's hydrological cycle, is also recognized for its importance in sustaining agricultural practices. 21% of respondents consider snowmelt to be a moderate influence on their water supply, while 8% believe it plays a lesser role, and 3% consider it to have an insignificant impact (Figure 7) (Pritchard, 2019). This variability in perceptions highlights the complex and interconnected nature of water sources in the valley, where both glacial and snowmelt contribute to the overall availability of water for agriculture. The critical role of snowmelt is particularly evident during the early growing season, when it supplements glacial meltwater and helps to sustain crops during periods of low precipitation.

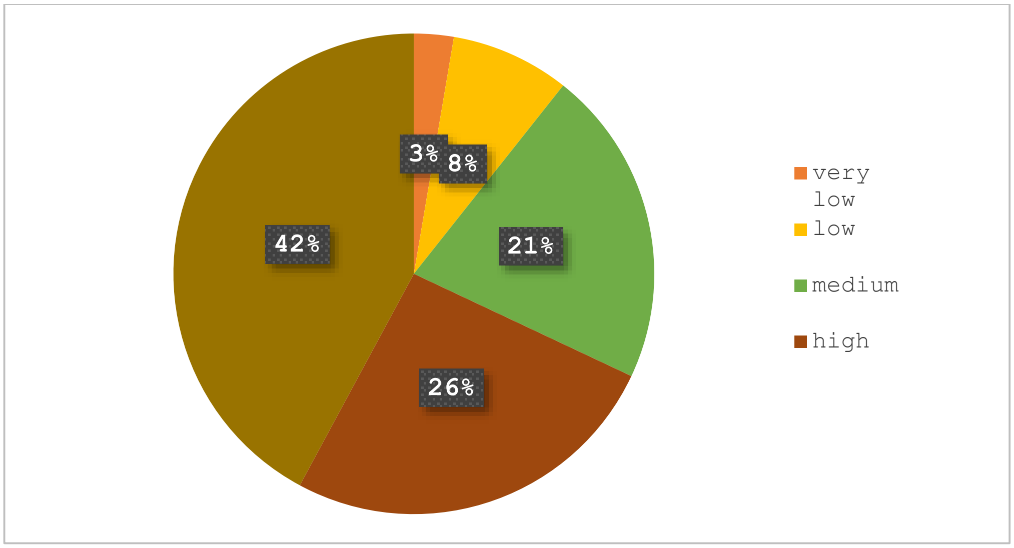


Figure 7. Perceptions of people about agriculture dependence on glacier meltwater.

The local community of the Shigar Valley has become increasingly aware of and concerned about the impacts of climate change, particularly its effects on the region's glaciers and the subsequent ramifications for agriculture and socioeconomic conditions. This awareness stems from the direct and observable changes in their environment, which have begun to disrupt the traditional patterns of water availability that their livelihoods depend upon. In a recent survey, a significant 78% of respondents reported a notable increase in water availability during the summer months, attributed to unprecedented snowmelt runoff. However, this surge in water flow is not without its drawbacks. The rapid melting of glaciers during the warmer months leads to excessive water flow that, while temporarily beneficial for irrigation, poses severe risks of flooding and soil erosion, ultimately threatening agricultural productivity and infrastructure stability (Kraaijenbrink et al., 2017; Vuille et al., 2018).

This seasonal imbalance in water availability highlights the complex challenges posed by climate change in glaciated regions. The excess water during summer is countered by a significant decrease in water availability during the winter, a time when consistent snowmelt traditionally provided a reliable source of water for irrigation. The shift in this delicate balance, driven by the accelerated melting of glaciers, is causing concern among local farmers who rely on consistent water supply throughout the year to sustain their crops. The reported scarcity of water during the winter months is particularly alarming as it directly affects the agricultural cycle, leading to reduced crop yields and heightened food insecurity (Immerzeel et al., 2010; Rasul et al., 2011). This pattern is consistent with broader observations across the Hindu Kush-Himalaya region, where communities are facing similar challenges due to changing hydrological cycles.

Interestingly, 20% of respondents noted an overall increase in total water availability, which could be interpreted as a short-term benefit. However, this perception may mask a more concerning long-term trend: the depletion of glacial reserves. As glaciers continue to melt at an accelerated rate, the temporary increase in water supply could eventually lead to the exhaustion of these critical water sources, resulting in severe water shortages in the future (Pritchard, 2019; Yao et al., 2012). This scenario underscores the paradoxical nature of climate change impacts in glaciated regions—where short-term gains in water availability could lead to long-term crises if the underlying causes of glacial depletion are not addressed. A minor percentage of respondents reported no major changes in water availability, which may reflect localized variations in glacial melt patterns or a lack of awareness of the broader regional impacts.

The community's growing concern about these changes is indicative of the broader socio-environmental challenges faced by mountainous regions globally, where the impacts of climate change are felt more acutely due to the dependency on natural water sources. The situation in the Shigar Valley calls for urgent adaptive strategies that not only address immediate water management needs but also consider the long-term sustainability of glacial resources. This includes enhancing local capacity for water storage during periods of excess, improving irrigation efficiency, and developing alternative water sources to reduce reliance on glacial melt (McDowell et al., 2013; Viviroli et al., 2011).

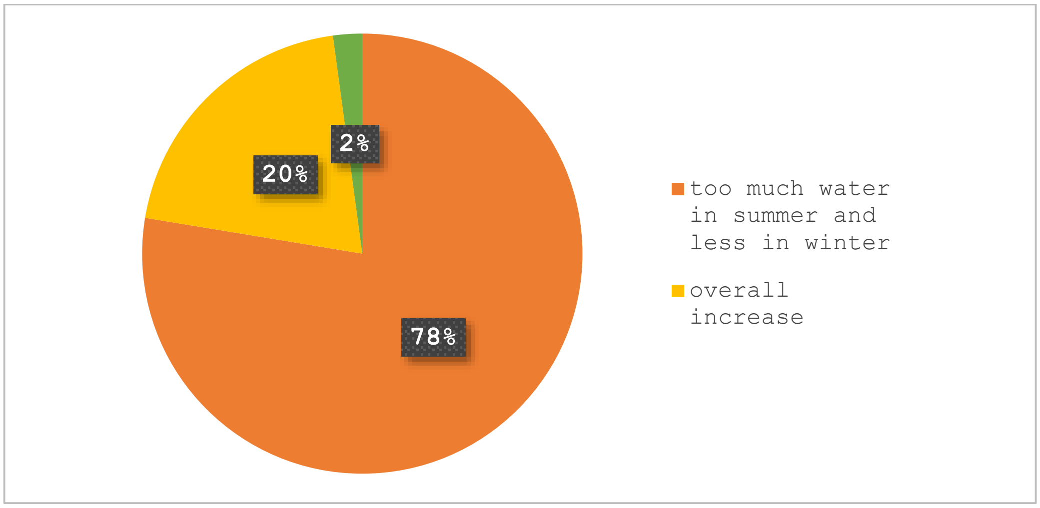


Figure 8. Perceptions of people about changes in the availability of water

Conclusion

The Shigar Valley in the Karakoram Range faces significant socio-economic challenges due to the changing glacier mass balance (GMB) driven by climate variability. As glaciers in this region are the primary sources of water, their accelerated melting and the associated impacts on water availability, agricultural productivity, and overall economic stability present a looming threat to the livelihoods of the valley's inhabitants. This study highlights the intricate relationship between glacial dynamics and the socio-economic fabric of the Shigar Valley, underscoring the critical need for comprehensive and adaptive management strategies to safeguard the future of this vulnerable region. The findings of this research emphasize the precarious nature of water resources in the Shigar Valley, which are becoming increasingly unreliable due to fluctuating GMB. The reliance of the local population on glacier meltwater for agriculture—an essential component of their livelihoods—places them at significant risk. The accelerated melting during warmer months, while providing temporary surges in water availability, is unsustainable in the long run and threatens the very foundation of the valley's agricultural productivity. Conversely, the reduced water flow in winter months creates challenges for irrigation, leading to potential crop failures and food insecurity.

The socio-economic impact of these changes is profound. Agriculture, which is the primary source of income for many households in the Shigar Valley, is being directly affected by the unpredictable water supply. The study reveals that a significant portion of the population experiences varying degrees of water scarcity, directly influencing their agricultural output and overall economic well-being. The increasing frequency and intensity of glacial lake outburst floods (GLOFs) further exacerbate these challenges, posing severe risks to life, property, and infrastructure. The threat of GLOFs not only disrupts the lives of those living in the valley but also imposes additional economic burdens on the community through the loss of crops, livestock, and homes.

Moreover, the irregular meltwater flows are also detrimental to the valley's hydropower potential. The variability in water availability hampers the consistent generation of hydroelectric power, which is crucial for supporting both domestic energy needs and potential industrial development. This inconsistency in energy supply further limits the valley's capacity to improve living standards and reduce economic vulnerability. The emerging tourism sector, which holds promise for economic diversification, is also at risk due to the changing GMB. The valley's stunning glacial landscapes, which attract tourists, are under threat from the same forces that jeopardize the local water supply. As glaciers retreat or become less stable, the very attractions that draw visitors may diminish, impacting the local economy and reducing opportunities for income diversification. In light of these challenges, it is imperative to develop proactive and sustainable strategies that address the multifaceted impacts of glacier mass balance fluctuations. Enhancing the understanding of glacial dynamics through continued research is crucial for predicting future changes and their potential effects on the valley's socio-economic conditions. Early warning systems for GLOFs and other glacial-related hazards must be strengthened to mitigate risks and protect the local population.

Adaptation strategies in agriculture, such as the development of water-efficient practices and the introduction of more resilient crop varieties, can help buffer the effects of water scarcity. Investment in infrastructure, particularly in the energy and tourism sectors, is necessary to build resilience against the economic impacts of glacial changes. Diversifying the local economy beyond agriculture and tourism, perhaps through the development of small-scale industries or other forms of sustainable economic activity, could also reduce the region's vulnerability to environmental changes.

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