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# Himalayan glacier response to climate variability: A study of the Ravi and Bhaga basins

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**Abstract**
The rapid melting of Himalayan glaciers from 1992 to 2020 is a significant indicator of climate change's impact on water supplies and mountain landscapes. The Ravi and Bhaga basins in the northern western Himalayas have experienced significant warming, with the Bhaga basin showing a linear trend of 0.025x + 264.1 and the Ravi basin showing a robust trend of 0.02x + 279. These trends align with satellite observations and meteorological records, which report mean temperature increases of up to 2 °C since the late twentieth century. Rising temperatures intensify glacier ablation by extending the duration and severity of the melt season, accelerating both surface and subsurface ice loss. Precipitation variability in both basins is weakly positive but not significant long-term. This results in consistently negative glacier mass balances, highlighting the need for adaptive spatial and temporal monitoring on glacier health.

**Keywords:** Himalayan glaciers, climate change, glacier mass balance, temperature variability

## Introduction

Himalayan glaciers function as vital freshwater reservoirs, playing a crucial role in buffering seasonal water flows and sustaining diverse socio-economic activities, including agriculture, hydropower generation, and biodiversity conservation across South Asia (Bolch *et al*., 2012; Immerzeel *et al*., 2012) [5, 20]. The Ravi and Bhaga basins, located within the rugged northwest Himalaya, exemplify glacierized catchments where complex topography and highly variable climatic conditions converge, making them ideal natural laboratories to study regional glacier dynamics and climate-glacier interactions (Adhikari *et al*., 2018; Kulkarni and Karyakarte, 2014) [1, 24].

Over recent decades, increased scientific attention has focused on the alarming acceleration of glacier recession throughout the Himalayan region, attributed primarily to atmospheric warming and alterations in precipitation regimes (Mukherjee *et al*., 2018; Pandey *et al*., 2013; Shekhar *et al*., 2010) [27, 30, 36]. Especially, these climatic changes have manifested as upward shifts in snowline altitude, negative mass balance, and altered surface energy fluxes, factors that collectively exacerbate glacier thinning and retreat (Gardelle *et al*., 2013; Kääb *et al*., 2012) [13, 22]. Despite the broad heterogeneity in glacier type, size, and debris cover, the overriding trend is one of sustained glacier shrinkage, increasing velocity gradients, and heightened thermal sensitivity, particularly evident since the early 2000s (Bhambri *et al*., 2017, 2012; Huss and Hock, 2018) [4, 18].

The Bhaga basin, for example, has exhibited a significant reduction in glacierized area-most recently quantified as a shrinkage of approximately 8.3±1.5% between 1971 and 2020, with an average annual glacier area loss rate nearly doubling from −0.14% per year before 2000 to −0.21% per year subsequently (Das *et al*., 2022; Shukla *et al*., 2021) [38, 9]. Similarly, glacier retreat patterns in the Ravi basin confirm these region-wide signals, where atmospheric warming has emerged as the dominant forcing mechanism over precipitation variability (Adhikari *et al*., 2018; Gaddam *et al*., 2020; Gopika *et al*., 2021; Kulkarni and Karyakarte, 2014) [1, 12, 14, 24].

Glacier dynamics in these basins are strongly modulated by intrinsic factors such as glacier size, slope, aspect, and debris coverage. South-facing glaciers and those with extensive supraglacial debris tend to retreat faster due to enhanced surface ablation and energy absorption (Nagai *et al*., 2013; Sakai *et al*., 2015, 2002; Tewari *et al*., 2017) [28, 35, 40]. The growth of supraglacial and proglacial lakes also exacerbates mass loss through increased calving and localized melting, compounding the vulnerability of these glaciers (Bhambri *et al*., 2017; Dobhal *et al*., 2021; Shugar *et al*., 2017) [4, 11].

The cumulative effects of ice thinning, tributary glacier detachment, and exposure of lateral moraines indicate a marked negative mass balance and geomorphological transformation in the Ravi and Bhaga basins. These processes not only signify the glaciers' heightened sensitivity to ongoing climatic perturbations but also highlight the critical need for basin-scale, long-term glacier-monitoring networks and high-resolution modeling frameworks. Such efforts are indispensable for precise predictions of future water availability, glacier-driven hazards, and landscape dynamics, thereby supporting sustainable resource management and climate adaptation strategies in this climate-sensitive region (Immerzeel *et al*., 2020; Shukla *et al*., 2021) [19, 38].

## Study Area

The Ravi and Bhaga basins, situated in Himachal Pradesh, span elevations from approximately 2,800 to over 6,000 meters, encompassing a mosaic of valley, cirque, and debris-covered glaciers. The Bhaga basin is marked by higher peaks and pronounced seasonal precipitation influenced by western disturbances, while the Ravi basin features complex glacier catchments, prominent proglacial lakes, and steep alpine valleys. The glaciers in these basins exhibit high variability in terms of elevation, slope, aspect, debris cover, and size-factors that govern their sensitivity to external climate drivers. Both basins drain into the Upper Indus River system, positioning them as significant contributors to regional water resources and downstream ecosystem services. Recent fieldwork and satellite-based inventories have mapped over 150 glacier entities in these regions, with the largest glaciers presenting measurable evidence of detachment, thinning, and length reduction over the study period (Chand and Sharma, 2015; Das and Sharma, 2019a; Pandey *et al*., 2017) [6, 7, 29].

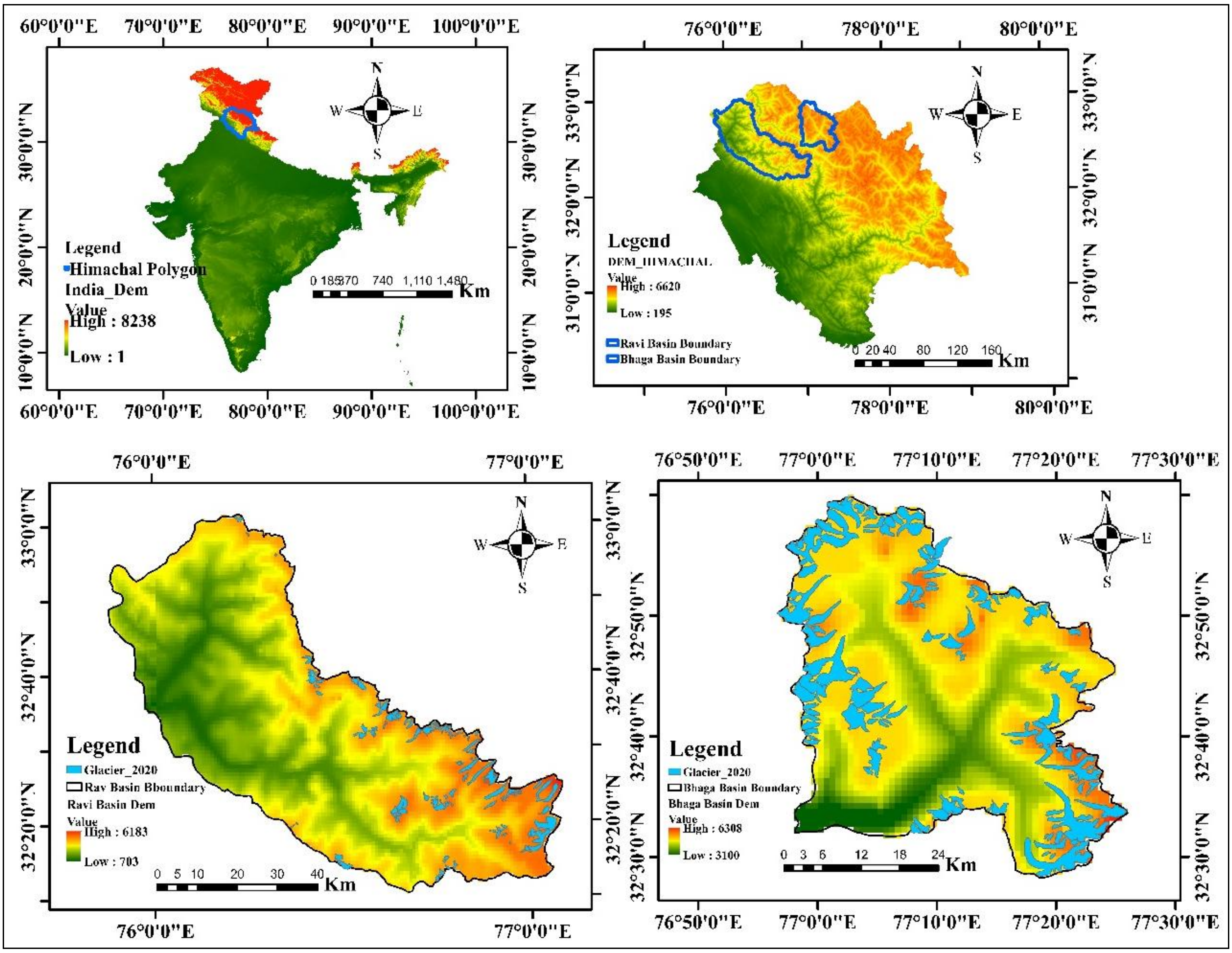


**Fig 1:** Location map of study area

## Methodology

This study utilized multi-source datasets including Landsat and MODIS satellite images, and SRTM-C digital elevation models, and glacier outlines from GLIMS and RGI (Raup *et al*., 2007) [33]. Glacier thickness changes were derived from DEM differencing, while glacier area and length changes were mapped using a combination of manual digitization and automated GIS methods (Dobhal and Mehta, 2010; Pellitero *et al*., 2015) [10, 31]. Glaciers were classified based on morphology, slope, and debris cover to analyze diverse recession patterns. Climate data on temperature and precipitation were obtained from ERA5 reanalysis and regional weather stations, then spatially interpolated for consistency across complex terrain. To ensure data reliability, glacier outlines and area measurements were cross-validated, and conservative error propagation was applied to address uncertainties from satellite and geodetic sources (Hersbach *et al*., 2020; Hoffmann *et al*., 2019; Radić and Hock, 2006) [16, 17, 32].

**Results and Discussion**

The analysis reveals that glacierized area in the Ravi basin declined from approximately 368.6±9.2 $km^2$ in 1994 to 353.0±5.3 $km^2$ in 2020, representing a total shrinkage of 4.2±2.9% at a mean annual rate of 0.16±0.11% per year. Analogously, the Bhaga basin saw a reduction of about 8.3±1.5% in glacierized area from 1971 to 2020, with the loss rate doubling post-2000 (Das and Sharma, 2019b) [8]. Especially, debris-covered glaciers exhibited both slower area loss and increased thickness reduction due to their altered energy absorption dynamics. The retreat rate of the largest valley glaciers was found to accelerate, rising from ~9.3±1.9 m $yr^{-1}$ during 1994-2006 to ~13.3±1.8 m $yr^{-1}$ during 2006-2020, emphasizing heightened thermal sensitivity since 2000. Regional warming-estimated at 1-2 °C since the 1990s-and reduced snowfall, alongside episodes of intense summer ablation and altered monsoon patterns, emerged as primary climate drivers (Angchuk *et al*., 2021; Mishra *et al*., 2023) [2, 26]. Differentiation among individual glacier response times reflected their size, slope, and debris characteristics; glaciers lower in elevation and with greater debris cover responded more rapidly to warming. Increased occurrence of proglacial and supraglacial lakes promoted terminus calving and exacerbated melting. This persistent recession signifies a transformation of glacier-fed hydrological regimes, with immediate increases in meltwater followed by long-term threats of diminished runoff and river discharge (Guha *et al*., 2024) [15].

Recent multi-decadal satellite observations and ground-based glacier inventories indicate pronounced recession in the glaciers of the Ravi and Bhaga basins between 1992 and 2020, with area loss accelerating particularly after 2000. In the Bhaga basin, the glacierized area was reduced from 362.9±4.0 km² in 1971 to 332.7±3.6 km² in 2020-a decrease of 8.3±1.5%-and with the mean annual area loss rate increasing from −0.14%/yr (1971-2000) to −0.21%/yr (2000-2020) (Chand and Sharma, 2015; Das and Sharma, 2019a) [6, 7]. In the Ravi basin, the mean area vacated by glaciers per year was estimated at approximately 0.23 km²/yr during recent decades.

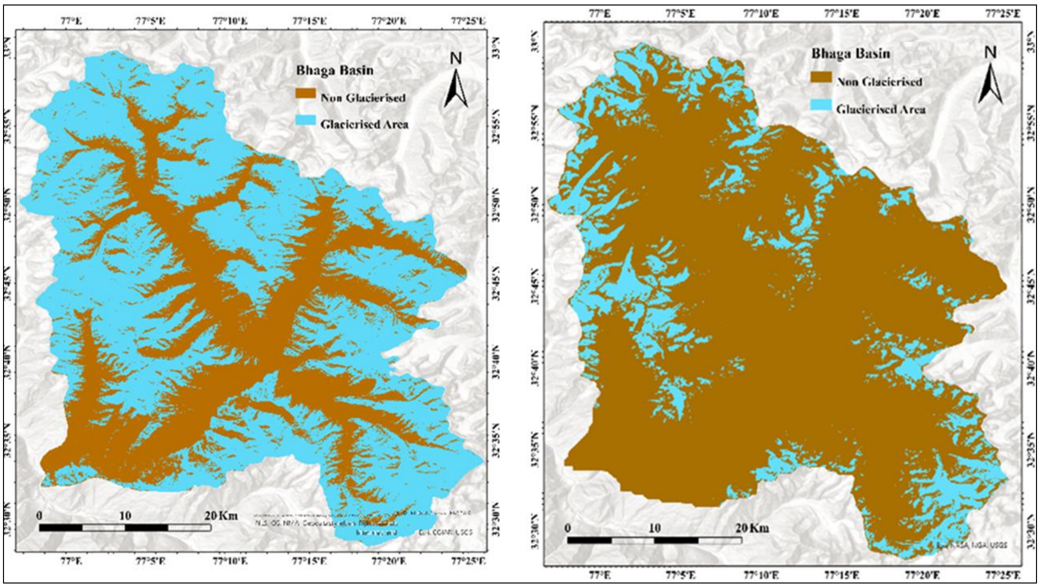


**Fig 2:** Variation in glacier area of Bhaga basin 1994(left) and 2020 (right).

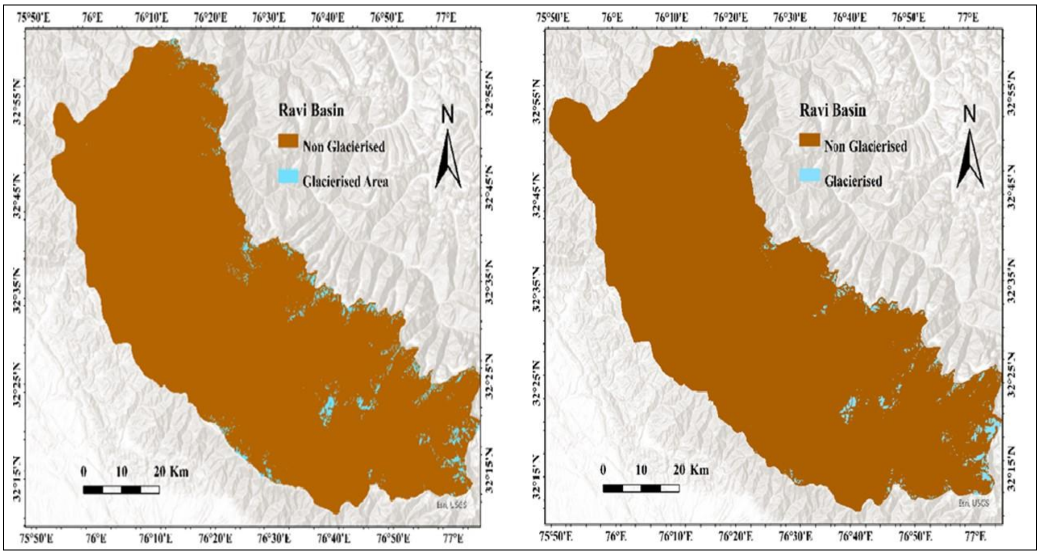


**Fig 3:** Variation in glacier area of Ravi basin 1994(left) and 2020 (right).

The primary driver behind this acceleration is regional climate warming, coupled with shifts in precipitation patterns. Regional climate records demonstrate that the northwestern Himalaya-including the Ravi and Bhaga basins-experienced mean annual temperature rises of approximately 1 °C to 2 °C over the past 30-40 years, with warming rates as high as 3-4 °C per century in the most recent two decades. Studies analyzing MODIS Land Surface Temperature data for 2000-2014 report mean annual temperatures of 5.38 °C with summer maxima exceeding 16 °C in the broader region, intensifying melt during ablation seasons (IPCC, 2018; Mir *et al*., 2015). Maximum temperature increases of 1.0-2.0 °C and minimum increases of up to 3.4 °C have also been documented in mountain ranges adjacent to the Bhaga basin from 1988 to 2008, underscoring strong warming signals amplified at high elevations.

In parallel with temperature trends, precipitation (particularly winter snow accumulation) declined through much of the late twentieth century, limiting accumulation in glacier high zones. Although a slight recovery or variability has been observed in the past decade, the imbalance between increased ablation (driven by warming) and relatively stagnant accumulation has resulted in enhanced negative glacier mass balance. Geodetic studies confirm mean elevation and thickness declines of -0.35±0.33 m/yr between 2000 and 2012 across the upper Indus region. Glaciers in the Bhaga basin were found to have a mean frontal retreat rate that increased from 9.3±1.9 m/yr (1994-2006) to 13.3±1.8 m/yr (2006-2020), clearly correlating with the intensified warming period (Kaushik *et al*., 2020; Pandey *et al*., 2017; Snehmani *et al*., 2016) [23, 29, 39].

The effects of warming are especially acute for glaciers at lower elevations, south-facing slopes, and those with significant debris cover. Glaciers with debris mantles tended to experience more rapid thinning, even if lateral retreat was less pronounced, due to differential melting under the insulated debris layer. The development and expansion of proglacial and supraglacial lakes linked to increased ablation and thermokarst processes have further hastened mass loss by exposing ice margins to localized heating and calving effects.

furthermore, the convergence of multi-source data reveals that climate warming manifest as both record high summer and increased winter mean temperatures remains the chief driver of glacier wastage in both Ravi and Bhaga basins over the last three decades. The resulting shrinkage in glacier length, area, and thickness holds significant implications for river hydrology, basin-scale runoff, and the broader water security of downstream communities dependent on Himalayan meltwaters.

**Glacier Response to Climate Variability**

Long-term climate records from the Bhaga and Ravi basins reveal a steady rise in mean annual air temperature and significant variability in precipitation, both of which are critical drivers of glacier retreat in the northwestern Himalaya.

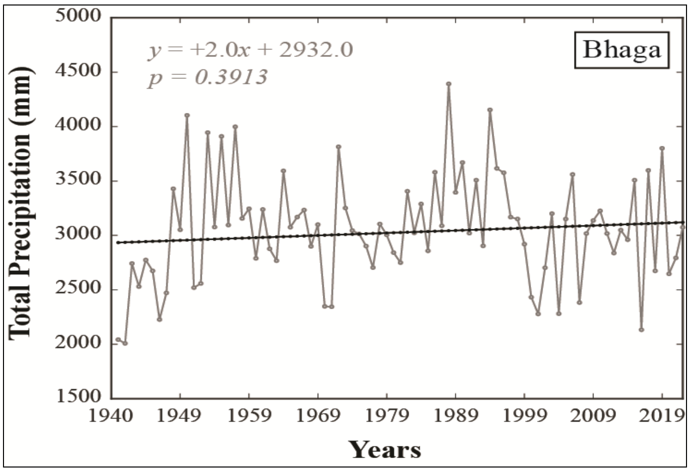


**Fig 4:** Total precipitation (mm) of the Bhaga basi

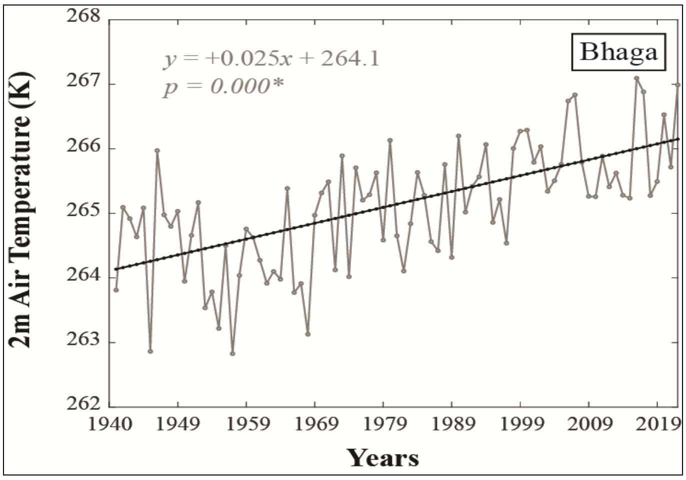


**Fig 5:** 2 m air temperature (K) of the Bhaga basin.

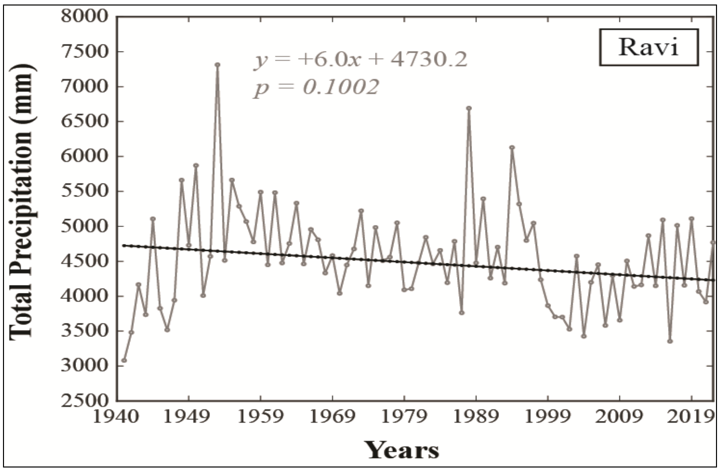


**Fig 6:** Total precipitation (mm) of the Ravi basin

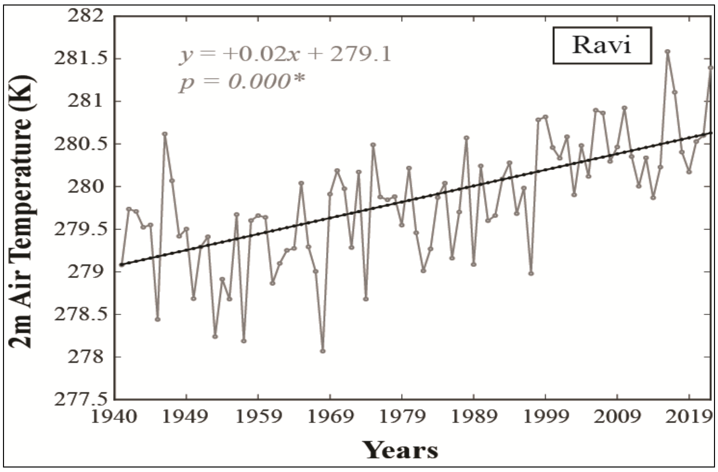


**Fig 7:** 2 m air temperature (K) of the Ravi basin.

**Temperature Trends**

The Bhaga basin exhibited a statistically significant rise in 2 m air temperature, with a linear trend of y = 0.025x + 264.1 ($p$=0.000), indicating highly significant warming between 1940 and 2019. Similarly, the Ravi basin showed a robust warming signal, with a trend of y = 0.02x + 279.1 ($p$=0.000), confirming strong and sustained temperature increases in recent decades. These upward shifts in atmospheric temperature align with both satellite observations and instrumental meteorological records, which report mean temperature increases of up to 2 °C since the late twentieth century

Rising temperatures intensify glacier ablation by extending the duration and severity of the melt season, accelerating both surface and subsurface ice loss. The pronounced warming observed in both basins closely aligns with documented glacier recession, area reduction, and mass thinning, underscoring the critical influence of thermal factors in driving glacier decline.

**Precipitation Variability**

The Bhaga basin shows a weakly positive precipitation trend (y = 2.0x + 2932.0), but the non-significant p-value (0.3913) indicates no meaningful long-term change, with totals fluctuating widely. Conversely, the Ravi basin exhibits a slight negative trend in annual precipitation (y = -6.0x + 4730.2), though again statistically non-significant ($p$=0.1002), reflecting strong interannual variability without a consistent directional shift.

Although precipitation fluctuates, reduced snowfall or stagnant totals are insufficient to offset the intensified melt from rising temperatures, resulting in consistently negative glacier mass balances. This interaction between warming and non-compensating precipitation accelerates ice loss and reshapes glaciated landscapes.

**Cumulative Impacts on Glacier Dynamicss**

The inescapable warming and precipitation variability in the Bhaga and Ravi basins mirror broader Himalayan trends, confirming that rising temperatures are the prime climatic driver of glacier recession, while precipitation particularly winter snowfall and rainfall acts as a secondary, modulating factor. These results are consistent with remote sensing and geodetic evidence of 4-8% glacier area loss and accelerated frontal retreat since the early 1990s.

Such patterns highlight the acute vulnerability of Himalayan glaciers to warming-induced ablation, with far-reaching consequences for downstream water security and ecosystem stability. Sustained monitoring of basin-specific climate indicators, coupled with detailed glacier change assessments, is vital for improving projections and informing adaptive water resource management across mountain catchments.

**Conclusion**

The Ravi and Bhaga basins have experienced measurable and accelerating glacier recession over the past three decades, as evidenced by declines in area, length, and thickness. The dominant climate driver is climate warming, compounded by reduced precipitation phase (changes in snowfall and rainfall). Consequences extend to downstream water security, hydropower potential, and mountain ecosystem stability, highlighting the fundamental role of high-mountain glaciers in sustaining environmental and socioeconomic systems. To address these challenges, continued satellite and ground-based monitoring, improved glacier-climate modelling, and adaptive water resource management are recommended. This study demonstrates the complexity and urgency of understanding glacier dynamics in the Himalaya and provides a blueprint for future interdisciplinary research addressing the fate of mountain glaciers under advancing climate change.

The dominant driver is regional climate warming (mean increases of ~1-2 °C since the 1990s, with higher elevation amplification), which has lengthened and intensified melt seasons. Precipitation trends are highly variable and, where declining winter snowfall, have not compensated increased ablation; thus, net mass balance remains negative. Hydrological implications are two-fold: near-term increases in meltwater and runoff followed by long-term declines in glacier-fed discharge and altered seasonal flow regimes posing risks to downstream water security, irrigation, hydropower and ecosystems.

Overall statement the consistent multi-source evidence demonstrates that climate warming, amplified at high elevations, is the primary cause of glacier shrinkage in the Ravi and Bhaga basins. This ongoing recession will likely produce transient increases in runoff but ultimately diminish glacier contributions to river flow, with significant socio-environmental consequences unless adaptive management and continued monitoring are implemented.

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