Imminent threat to water resources of the Indus Basin under changing climate

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Abstract

Indus River Basin (IRB) provides water to millions of people living in upstream and downstream regions, playing a significant role in supporting agriculture and other ecosystem services. The basin is predominantly driven by two main precipitation regimes: Western Disturbances (WDs) and Indian Summer Monsoon (ISM), which contribute significantly to the annual precipitation. WDs account for over 70% of the precipitation, affecting western parts of the basin, while monsoon moisture exhibits considerable spatial variability, with some areas receiving up to 80% of their annual precipitation. Climate projections exhibited that IRB may experience an increase in annual liquid precipitation, particularly in high-altitude regions, but a decline in solid precipitation by the end of the 21st century. Concurrently, the region is experiencing significant warming, particularly in winter, with temperature projections predicting an increase of over 5°C by 2100. The hydrology of the IRB is intricately tied to the cryosphere, with glaciers, snow and permafrost providing crucial water reserves. The IRB contains over 18,495 glaciers, stores substantial amounts of water and provides around 70% of the water supply to the region. However, these cryospheric components are under retreating threat, with projections suggesting a decline of 15% to 60% by 2100. Groundwater recharge, highly dependent on cryospheric meltwater, is also at risk with reduced recharge rates. The combined impact of climate change-induced disruptions to water availability poses significant threats to agriculture, biodiversity and ecosystem services in the IRB. The growing water stress, coupled with shifting precipitation patterns, generates socio-economic vulnerabilities that necessitate urgent adaptive strategies for sustainable water management and climate resilience in the region.

Keywords: Climate; Glacier; Hydrology; Himalaya; Indus; Snow

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1. Introduction

The Hindukush-Karakoram-Himalaya (HKH) region, spanning over 4 million km^2, represents one of the Earth's largest and most complex mountain systems. It stretches across the rugged terrains of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan (Bajracharya and Shrestha, 2011; Wester et al., 2019). The HKH directly sustains the livelihoods of over 240 million people living upstream and indirectly benefits about 2 billion people downstream, underscoring its vital importance to the socio-economic and ecological fabric of the region (Wester et al., 2019). Meltwater from the HKH feeds 10 major river basins across Asia, covering a combined area of nearly 8.9 million km^2. These basins include: Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze and Yellow River basins. Among these, the Indus River Basin (IRB) stands out as the second largest after the Yangtze, with a transboundary expanse of approximately 1.12 million km^2 spanning Afghanistan, China, India and Pakistan (Bajracharya and Shrestha, 2011). The basin hosts the world's largest irrigation system, spanning over >2,00,000 km^2, sustaining vast agricultural fields downstream. Approximately 237 million people benefit directly or indirectly from the ecological and hydrological resources of the IRB, with the majority residing in Pakistan (61%), India (35%), Afghanistan (4%), and China (Laghari et al., 2012). Based upon the geomorphological setup and altitudinal gradients, IRB can be characterized into two primary zones: Upper Indus Basin, comprising the mountainous regions of the Hindukush, Karakoram and Himalayas, hosting most of the glacier and snowfields, and Lower Indus Basin, representing the southern arid plains, hydrologically dependent on upstream water resources (Immerzeel et al., 2010).

The water resources of the IRB are increasingly under threat from the multi-faceted impacts of climate change (Lone and Jeelani, 2023). Rising temperatures and shifts in precipitation patterns are altering seasonal evapotranspiration trends, glacier volume and snowmelt dynamics, thereby disrupting the hydrological regime of the region (Bolch et al., 2012; Lutz et al., 2014; Nepal and Shrestha, 2015). For example, permafrost degradation, water tables decline, drying of surface waterbodies and diminishing spring flows are compounded by more frequent and severe weather extremes (Jeelani et al., 2024; Jeelani and Deshpande, 2024). Hydrological regimes are further stressed by the changing form of precipitation, from snow to rain which not only reduces seasonal snow accumulation but also exacerbates flash floods and erosion during periods of intense rainfall (Lutz et al., 2014; Nepal and Shrestha, 2015). The transboundary nature of the IRB adds a layer of political sensitivity between the neighbouring countries. The partitioning of stream water is already a matter of huge context, with treaties such as the Indus Waters Treaty attempting to govern the equitable distribution of water between India and Pakistan. However, disputes remain over shared resources, compounded by gaps in the understanding of regional groundwater dynamics and recharge processes (Mukherjee et al., 2015; Cheema and Qamar, 2019). Addressing these gaps is critical for fostering cooperative water management and mitigating potential conflicts. Despite its critical importance in sustaining the lives and livelihood of millions living in IRB, significant knowledge gaps persist, particularly concerning the hydraulic connections between surface and groundwater systems and their behavior under changing climatic scenarios. Comprehensive hydrological data collection and analysis are essential for improving regional water resource management policies. Advanced hydrological models, remote sensing and field studies are necessary to predict future water availability and mitigate risks associated with climate variability.

2. Physiographic setup and climatic conditions

The Indus River Basin (IRB) encompasses an extremely diverse topography, ranging from high-altitude mountain ranges in the north to vast plains in the south. This geographical complexity, shaped by tectonic processes and varying climatic conditions, profoundly impacts the inter and intra-hydrology and climatic conditions of the basin. The northern parts of the IRB, including the Kabul Basin, Upper Indus Basin and upper reaches of the Punjnad Basin, consist of highly elevated terrains dominated by the Pir-Panjal, Himalaya, Karakoram and Hindukush mountainous ranges (Fig. 1). These ranges run nearly parallel, creating longitudinal valleys such as Jhelum, Gilgit, Shyok and Indus valleys. The UIB features some major peaks such, as K2 (8611 m, asl) and Nanga Parbat (8126 m, asl), while other notable summits include Shahi-Kangri (6934 m, asl) in the Shyok sub-basin, Nun (7135 m, asl) in the Chenab sub-basin and Batura Muztagh (7795 m, asl) in the Gilgit sub-basin.

Moving southward, the basin transitions into the Lower Indus Basin (LIB), characterized by the low-lying terrains and fertile plains of Sindh and Punjab, which are part of the Himalayan Foreland Basin (Fig. 1). Below the Pir-Panjal range lies the less elevated Siwalik Range, composed predominantly of siliciclastic sediments, followed by a narrow strip of foothill plains that gradually merge into the wide plains of the IRB (Burbank et al., 1996; Nanda et al., 2018). The complex topography of the IRB gives rise to significant climatic variability. The northern highlands experience an alpine climate, marked by heavy snowfall and cold temperatures. However, towards the south, the climate transitions through subtropical, arid, semi-arid and eventually temperate sub-humid conditions in the lower plains (FAO, Aquastat, 2011; Mehmood et al., 2022). The southern slopes of the upper Indus basin exhibit a subtropical climate, characterized by moderate temperatures and seasonal rainfall. The north-eastern regions of the UIB, such as Ladakh, lie in the rain-shadow zone of the Himalayan and Karakoram ranges, resulting in starkly arid climatic conditions (Bookhagen and Burbank, 2006; Laghari et al., 2012).

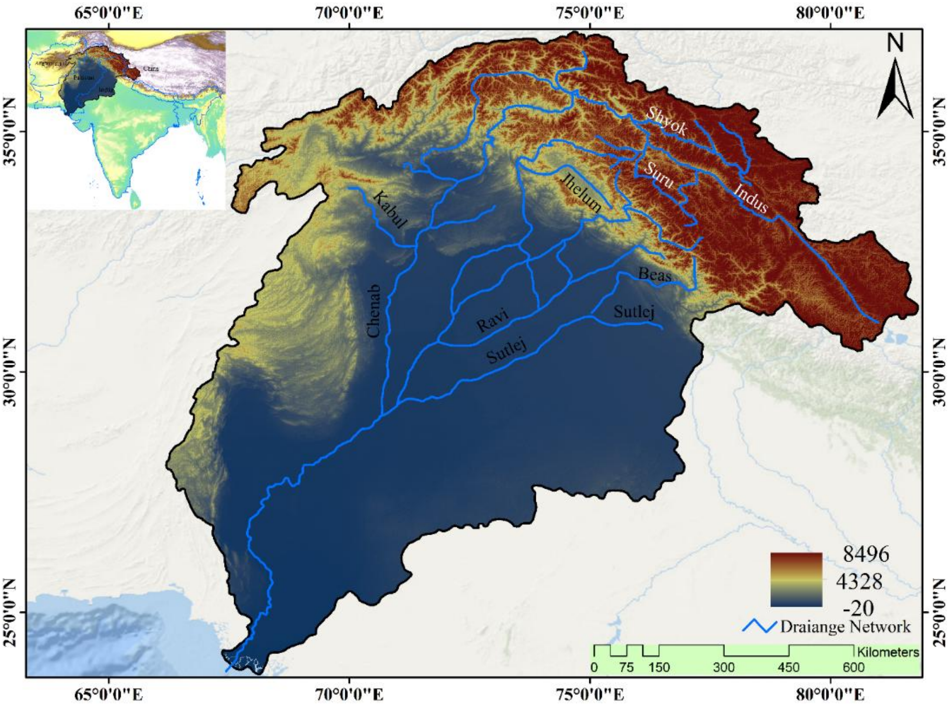

Figure 1. Physiographic setup and major drainage network of Indus River Basin (IRB). Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) is used as a base map (https://earthexplorer.usgs.gov).

The altitudinal range (0 to 8611 m, asl) contributes to highly variable precipitation patterns, ranging from as low as 60 mm in cold-arid zones to over 2000 mm in the high-altitude regions (Ojeh, 2006; Dimri et al., 2020). Western Disturbances dominate the hydrology of the northern IRB, contributing over 70% of annual precipitation in the form of snow during winter and spring (Bengtsson et al., 2006; Pang et al., 2014; Hasson et al., 2017; Jeelani et al., 2017a; Lone et al., 2023). Western disturbances are particularly influential in the Karakoram region, ensuring a steady winter snowpack critical for glacier sustenance. The Karakoram and north-western highlands dominated by WDs, receive most of their precipitation in winter, sustaining the snowpack and glaciers that feed the Indus River. While as, the Great Himalayan region experiences heavy monsoonal rainfall, crucial for irrigation and groundwater recharge in the southern plains (Fowler and Archer, 2005; Bookhagen and Burbank, 2010; Tahir et al., 2011; Latif et al., 2021). The interaction between WDs and ISM generates complex hydro-meteorological conditions that govern the availability and distribution of water resources in the region (Jeelani et al., 2017b). The northern highlands, with their reliance on winter snow, provide meltwater critical for sustaining river flow during the dry seasons. Conversely, the southern plains depend on monsoonal rainfall for agriculture and groundwater replenishment (Dimri et al., 2020). These interactions emphasize the regional dependence on both weather systems and highlight the sensitivity of its water resources to climate dynamics (Hunt et al., 2024).

3. Hydrometeorology of the Indus River basin

The precipitation in South Asia, including IRB, is predominantly influenced by two major precipitation regimes: WDs and ISM, which serve as the primary source of moisture for the region. The significant temporal variability in precipitation, particularly during summer and winter, has been observed across various periods (1961-1990, 1951-2010, and 1986-2010), highlighting the complexity of meteorological changes and their controlling factors (Archer and Fowler, 2004; Hartmann and Andresky, 2013). In UIB, precipitation is projected to increase by approximately 25% between 2046 and 2065, with the wettest months (February to April) experiencing sharp intensity (Immerzeel et al., 2010; Forsythe et al., 2014). Studies have predicted an overall increase in precipitation, although with varying results based on modeling approaches (Akhtar et al., 2008; Forsythe et al., 2014). Long-term precipitation data does not indicate significant trends or patterns (Anders et al., 2006; Bhutiyani et al., 2007; Lone et al., 2022), yet climate projections suggest rises in annual as well as seasonal precipitation towards the mid-to-late 21st century (Ahmed et al., 2020; Benerjee et al., 2020). Notably, studies indicate that high-altitude regions will likely see increased mean annual precipitation and stronger monsoon activity, while winter and spring precipitation are expected to decline by the end of the century (Shrestha et al., 2019; Lone et al., 2021). Temperature trends in the IRB reveal heterogeneous results (Bhutiyani et al., 2007). Summer minimum and mean temperatures have shown consistent decreases, whereas maximum summer temperatures exhibit no discernible trend from 1961 to 2000. In contrast, winter maximum and mean temperatures have increased significantly, with winter minimum temperatures showing no consistent pattern (Fowler and Archer, 2006). Between 1976 and 2005, a rise of over 1°C in maximum winter temperatures was reported across all parts of the IRB (Khattak et al., 2011; Lone et al., 2019). Over the past few decades, mean annual temperatures in the Himalayas have increased by 0.32°C per decade, higher than the global average of 0.19°C per decade. Winter warming exceeds summer warming in this region (Bhutiyani et al., 2007; Yao et al., 2022; Jeelani and Deshpande, 2024). In the southern plains of the IRB, a significant annual mean temperature increase of approximately 0.50°C was observed between 1960 and 2007 (Chaudhry and Rasul, 2007). Climate models, including general circulation models (GCMs) and regional circulation models (RCMs), project an increase of over 5°C in the upper IRB by the century's end (Shrestha et al., 2019). Projections for minimum and maximum temperatures in northern and southwestern IRB regions also indicate increases (Kazmi et al., 2014). The long-term temperature data for the IRB reveals a significant yet regionally distinct warming trend across different periods. Over the last century, warming in the region ranged from 0.9°C to 1.6°C, with the majority occurring in the past 50 years (Gautam et al., 2013). Projections based on CMIP5 models suggest daily average temperature increases of 2.1°C to 2.9°C under RCP 4.5 and 8.5 scenarios, with higher increases anticipated during winter and in mountainous regions compared to summer and plains. The IRB comprises a complex network of rivers and tributaries (Lone et al., 2022a).

The Indus River originates from the Bokhar Chu Glacier in Tibet at an elevation of 4164 m, asl, covering a total length of 3180 km before merging into the Arabian Sea near Karachi (Shrestha et al., 2015). Major tributaries such as Nubra, Shyok and Gilgit join the Indus at various points, with snow cover, glacier melt and seasonal rain playing vital roles in regulating river discharge (Fig. 2, Savoskul and Smakhtin, 2013; Sharma et al., 2013; Jeelani et al., 2017a). The annual flow of the Indus River is approximately 210 km^3, with an average discharge of 6930 m^3/s (Lone et al., 2022b). The UIB contributes about 110 km^3 annually, accounting for half the total system flow (Lone et al., 2022a). Tributaries such as Shyok, Hunza and Shigar rivers originate from the Karakoram Range with respective discharge rates of 360 m^3/s, 330 m^3/s, and 200 m^3/s (Hasson et al., 2017). Other tributaries like Gilgit, Kabul, Zanskar, and Astore Rivers originate from the Hindukush and Greater Himalayas, contributing significant discharges (Mukhopadhyay and Khan, 2015). The Jhelum, Chenab, Ravi, Beas and Satluj rivers, originating from various Himalayan ranges in India, also play vital roles, with Chenab having the highest discharge among them (FAO-Aquastat, 2011; Lone et al., 2022a; Lone et al., 2022b).

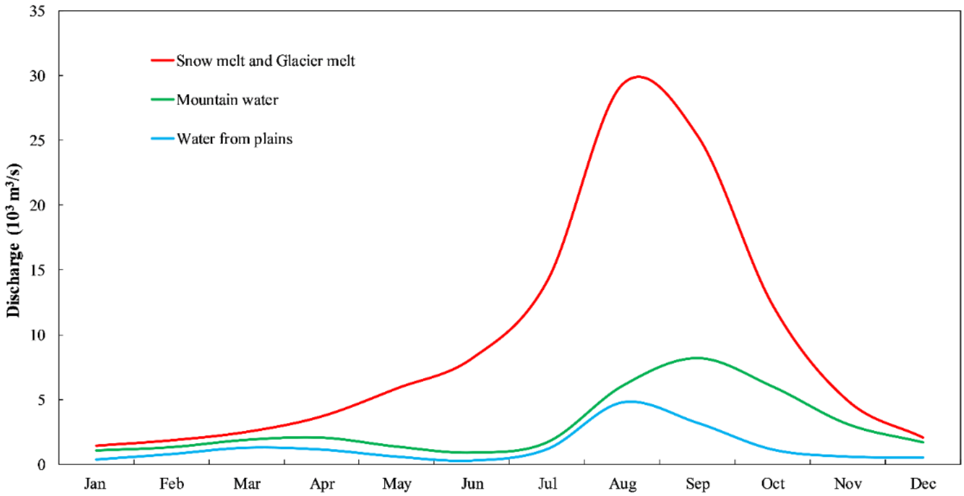

Figure 2. Daily mean contribution of total mountain water (rainfall run-off, snow and glacier melt originating from mountain areas), and snow and glacier melt only, to the total downstream discharge (after Biemans et al., 2019).

4. Cryospheric reserves and their controls

The cryosphere encompassing components, such as glaciers, snow, ice sheets and permafrost, play an essential role in regulating climate and acting as a sensitive indicator of climate change (Marshall, 2012; Mukherji et al., 2019). The IRB hosts approximately 18,495 glaciers, covering 21,192 km² and storing an estimated 1620 ± 340 Gt reserves of water (Bajracharya and Shrestha, 2011; Kulkarni et al., 2023). The Upper Indus Basin (UIB) with 11,413 glaciers (61.7% of the total) covers 71% of the glacier area and accounts for 80% of ice reserves (Fig. 3). Sub-basins like Shyok have the highest number of glaciers (3357), while Astore has less number of glaciers (372) (Bajracharya and Shrestha, 2011). The Upper Punjnad Basin (UPB) contains 5481 glaciers (29.8%), contributing 20.8% of the glacier area and 12.6% of ice reserves (Fig. 3). Among its sub-basins, Sutlej has the highest glacier count (2108), while Chenab boasts the largest glacier area (Yu et al., 2013; Mohammad et al., 2019). The Kabul Basin (KB), with 1601 glaciers (8.6%), represents 8.2% of the glacier area and 6.8% of the ice reserves (Bajracharya et al., 2019). Glaciers are vital for water availability, providing essential runoff for mid- and low-altitude regions, especially during the dry season (Kaser et al., 2010; Kour et al., 2016; Lone et al., 2017; Lone and Jeelani, 2024). Variations in glacier inventories, such as ICIMOD, RGI 6.0, and GAMDAM, highlight differences in spatial and temporal coverage, methodologies and findings. For example, RGI and GAMDAM report larger glacier cover than ICIMOD, underscoring the importance of region-specific inventories for effective water resource management (Bajracharya et al., 2019; Soheb et al., 2022; Giese et al., 2022). Permafrost, defined as ground remaining below 0°C for at least two years, covers approximately 22.7 million km² globally, constituting about 25% of the Northern Hemisphere's land surface (Zhang et al., 1999).

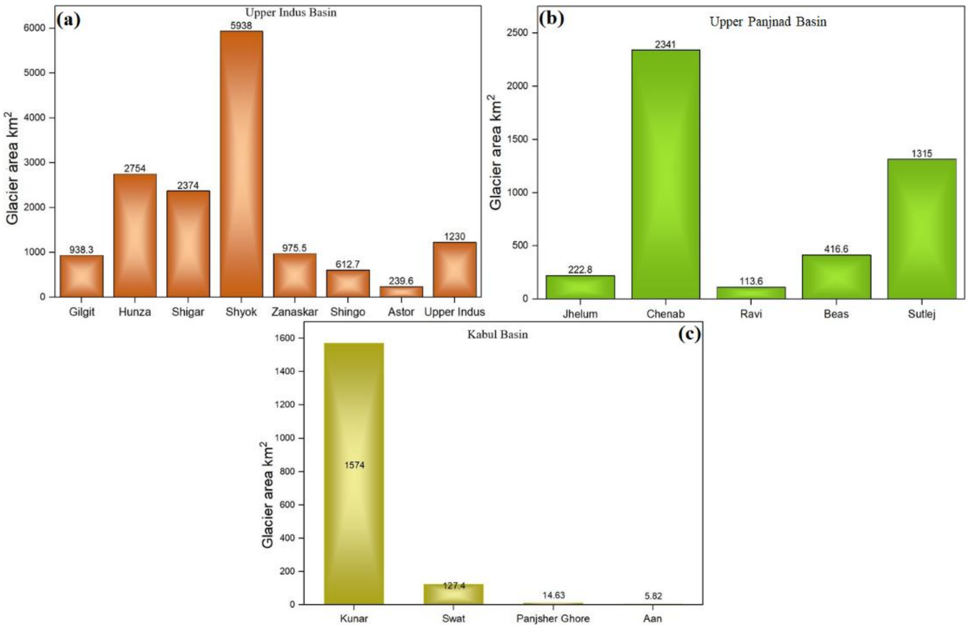

Figure 3. Glacier area (square kilometers) in different sub-basins of Upper Indus, Upper Panjnad and Kabul basins. The plot depicted that Upper Indus has high glacier cover, followed by Upper Panjnad and Kabul basins (after Bajracharya et al., 2019).

In arid regions, permafrost acts as an impermeable layer, preserving soil moisture and nutrients vital for ecosystems (Lu et al., 2017). The thermal state of permafrost is highly sensitive to climate change, making it a critical indicator of environmental shifts (Gruber and Haeberli, 2007; Etzelmüller, 2013). Studies in UIB indicated that 38% of the region contains continuous and discontinuous permafrost, while seasonal frost covers 15%. Using altitude-based models, researchers estimate that 45% of the UIB is underlain by permafrost, with its lower limit at an average elevation of 4919 ± 590 m, asl (Hassan et al., 2023). Local-scale studies in areas like Ladakh and the Tibetan Plateau confirm intermittent permafrost presence (Rastogi and Narayan, 1999; Wani et al., 2020). Snow, a crucial cryospheric component, plays a vital role in the hydrological and climatic systems of mountainous regions (Painter et al., 2009). Acting as a natural reservoir, it stores water in mid to high-altitude regions and contributes significantly to river runoff during the melt season (Dobreva et al., 2011; Jeelani and Deshpande, 2024). The snow cover of IRB exhibits significant spatio-temporal variations due to climatic and altitudinal diversity. Mountainous sub-basins such as Shigar, Astore, and Chenab exhibit the highest annual snow cover, while lower-altitude areas (Lower Indus Basin) lack snow precipitation. Sub-basins like Shigar and Hunza retain perennial snow and ice cover, while regions like Shyok, due to their low elevation, experience minimal snow accumulation (Archer, 2003). Seasonal variations are also prominent, with Astore and Gilgit having snow cover ranging from 2 ± 1% in summer to over 90% in spring. Similarly, Hunza and Shigar show a summer dip of 17-25%, with spring snow cover exceeding 80% (Immerzeel et al., 2009). In lower-altitude sub-basins like Jhelum and Kabul, snow cover varies from 1% in summer to over 75% in spring. Snowmelt is a significant contributor to runoff in the IRB, particularly in mid- and high-latitude regions. However, rising temperatures and declining precipitation have accelerated snowmelt, altering seasonal runoff patterns essential for irrigation, drinking water, and hydropower (Immerzeel et al., 2009). Recent studies indicate alarming reductions in snow cover, with annual losses of 458 km² in Chenab, 382 km² in Jhelum, 840 km² in the Upper Indus, and 2459 km² across the entire IRB. This decline threatens smaller rivers and exacerbates water scarcity in the region (Ali et al., 2020).

Meltwater, formed when snow and ice melt due to rising temperatures (Brown, 2002), is a critical freshwater source globally, especially in snow-covered and glacier-fed regions like the Indus River Basin (IRB) (Fig. 4). It contributes significantly to surface and subsurface hydrology, providing about 70% of water in the Upper Indus Basin (UIB) (Fig. 4, Immerzeel et al., 2010; Lone et al., 2021).

Glacier melt dominates UIB streamflow, accounting for 40.6% of total runoff (Lutz et al., 2014). Meltwater also sustains agriculture, contributing around 37% of the estimated 516 billion cubic meters of annual irrigation water withdrawals (Biemans et al., 2019). Unlike the rainfall-dominated Ganga and Brahmaputra basins, the IRB heavily depends on snowmelt, particularly in the western Himalayas, where snowmelt contributes 50% to runoff compared to less than 20% in the central and eastern Himalayas (Bookhagen et al., 2010). Groundwater, stored in subsurface pore spaces, is the second-largest freshwater resource after cryospheric reserves (Fitts, 2002). In IRB, cryospheric meltwater is the primary recharge source, with snowmelt and glacier melt contributing 35% and 50% to annual groundwater recharge in the UIB, respectively (Lone et al., 2021). In other basins, snowmelt accounts for 60% of recharge, while glacier melt contributes about 5% (Jeelani and Deshpande, 2024). The IRB encompasses a vast groundwater aquifer system spanning 16.2 million hectares. Currently, 38% of IRB land is irrigated using groundwater (Mehmood et al., 2022). This growing dependence, coupled with declining recharge rates, poses significant challenges to water sustainability in the region.

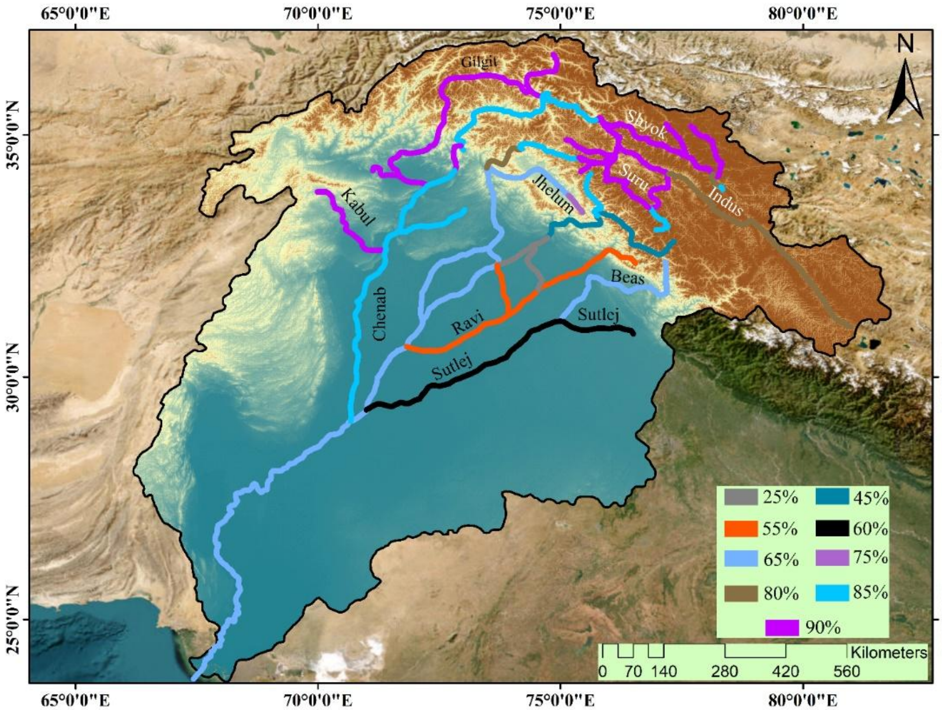

Figure 4. Snow and glacier melt contribution to streams originating from the different basins and sub-basins of the Indus, Panjnad and Kabul basins. The figure depicted that more than 80% of stream flow in upper reaches of Indus River Basin is dominated by snow and glaciermelt (after Biemans et al. 2019; Lone et al. 2022b).

5. Future hydrological regimes of IRB

Indus River Basin (IRB) is home to substantial freshwater reserves in the form of snow and glaciers, which are critical for the socio-economic stability and ecological integrity of the region. These resources not only sustain the livelihood of millions but also underpin agriculture, industry and ecosystem services. However, the changing climate is negatively affecting IRB, resulting in reshaping its hydrological and ecological dynamics. Recent studies highlight the significant threats posed by rising temperatures and shifting precipitation patterns in the region (Hussain et al., 2020). The Intergovernmental Panel on Climate Change (IPCC, 2021) projects that under an intermediate greenhouse gas emission scenario (SSP2-4.5), the global average temperature could rise by 2.1 to 3.5°C by 2100.

Such warming will lead to altered precipitation regimes, with longer, intense rainfall events interspersed with extended dry spells. Historical data from the region reveals a warming trend of 0.4°C per decade since the 1980s (Husain et al., 2021), with projections indicating an additional rise of 0.3°C to 0.7°C above global averages in the Himalayan region (Krishnan et al., 2019). In IRB, meltwater from snow and glaciers contributes substantially to hydrology, providing nearly 50% of the annual river flow, with 40% originating from glaciers and 60% from snowpack (Immerzeel et al., 2010). However, future projections under high-emission scenarios (RCP-8.5) suggest a 33% reduction in glacier area and a 50% decline in glacier volume by the end of the century (Immerzeel et al., 2013). These changes will profoundly impact the water supply, threatening the livelihoods of upstream and downstream communities and compromising the economic and ecological stability of the region. The water available from UIB supports agriculture, sustains ecosystems and provides vital ecosystem services that protect regional biodiversity and support human well-being. The water resources of IRB are projected to become highly variable under changing climatic conditions. Current and future meteorological data indicate that UIB will be particularly sensitive to the impacts of climate change, including more frequent extreme weather events. Erratic precipitation patterns and an increase in extreme events, such as glacial lake outbursts, snow avalanches and catastrophic floods, have already been observed. These events result in loss of life, displacement of communities and significant damage to infrastructure. Such disruptions are expected to escalate, creating greater socio-economic challenges. Future water availability projections for the IRB remain highly uncertain, with studies showing wide-ranging outcomes. The complexity of these interactions introduces significant uncertainties, with forecasts ranging from a 15% to 60% increase or decrease in water availability. This variability underscores the intricacy of climatic and hydrological factors influencing the basin. Groundwater, primarily recharged by meltwater, is equally vulnerable to climate change. Approximately 70% of streamflow and groundwater recharge in many UIB sub-basins depend on meltwater (Lone et al., 2021; Lone et al., 2022b). Changes in precipitation timing and distribution could disrupt seasonal recharge patterns, significantly reducing annual groundwater replenishment. This would have cascading effects on surface and subsurface hydrology, threatening biodiversity, ecosystem services and the overall sustainability of water resources in the region. The impacts of climate change extend beyond water resources to agriculture, which consumes approximately 90% of the water resources of IRB (Biemans et al., 2013). Major essential crops, including rice, wheat and cotton, are experiencing shifts in growing seasons and increased water stress due to rising evapotranspiration rates, which have increased by 3% to 6% over the last three decades (Lutz et al., 2014). These changes jeopardize food security and livelihoods of millions, creating socio-economic vulnerabilities. Water scarcity exacerbates the risk of regional instability, potentially escalating into interstate conflicts over shared resources.

6. Conclusion

Indus River Basin (IRB) is critically dependent on the cryospheric reserves which regulate water resources and support the socio-economic stability of the region. Glacier melt, snowmelt and permafrost-based recharge sources are key components sustaining agriculture and other ecosystem services. However, due to recent climate change, the IRB is facing severe challenges, leading to reduced water availability, disrupting the seasonal hydrological cycle and exacerbating water scarcity in upstream and downstream regions of the basin. Climatic projections, indicating a rise in temperature and a shift in precipitation, may reduce glacier volume and alter the runoff patterns of the region. Despite that some models are predicting an increase in water availability from higher precipitation, the overall impact of climate change is expected to be highly variable, with a potential decline in solid precipitation and changes in groundwater recharge that would exacerbate the pressure on groundwater resources, particularly in agricultural dominant regions. The vulnerability to climate change underscores the urgency of adaptive water management strategies. Addressing the growing risk of water scarcity and extreme weather events, such as floods and droughts, requires immediate action and long-term planning to ensure the sustainable use of water resources. Without effective interventions, the ongoing changes in the cryosphere will have significant ecological, economic and social consequences, potentially leading to increased regional instability and conflict over shared water resources. Therefore, it is crucial to develop comprehensive strategies for mitigating the effects of climate change and ensuring water security of the region.

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