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EDITORIAL

Threat to Himalayan Water Resources in a Changing Climate: Vulnerability and Fragility of Indus River Basin

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INTRODUCTION

The Hindukush Karakoram Himalaya (HKH) is one of the largest mountain systems on Earth spreading over parts of Afghanistan, Pakistan, India, China, Nepal, Bangladesh, Bhutan and Myanmar covering an area of 4,192,000 km^2. The Himalayan mountain ranges give birth to three major river basins viz, The Indus, the Ganges and the Tsangpo-Brahmaputra basin. These river systems sustain about 240 million people directly and more than 2 billion indirectly living in the region. The present Indus River is one of the world's longest rivers with a length of more than 3200 km running across China, India, Pakistan and Afghanistan. Shyok, Shigar, Gilgit and Kabul rivers are the major tributaries of the Indus River from the northwest and Jhelum, Chenab, Ravi, Beas and Sutlej rivers are the major tributaries from the northeast (Fig. 1). IRB, the second largest river basin (11,20,000 km^2) of Asia, constitutes a complex system of rivers and tributaries draining thirteen sub-basins with their origins from melt waters of Himalayan cryosphere (Lone et al., 2022).

The IRB hosts large number of glaciers, snow cover, permafrost and lakes. The Indus River system provides sustenance directly to millions of people living the mountainous region, and benefits 1.9 billion people downstream (Orr et al., 2022). However, during the last few decades, IRB has experienced significant and rapid climate warming. Shrinking and thinning glaciers, decreasing snow cover area, changing precipitation pattern and form, degradation of permafrost, shifting of stream flow peaks, attenuation or drying up of springs, lowering of water table, increase in extreme precipitation events, etc., are some of the dominant indicators of climate change in IRB. Understanding these changes and the associated complex interactions with other components like the atmosphere, hydrosphere, cryosphere and biosphere, are very vital in securing the lives and livelihoods of people living in the region. In this editorial we have briefly reviewed existing information on the water resources of IRB and explored the impact of climate change on these water resources. We also tried to identify the challenging and concerning areas to be studied, and future research priorities to be pursued to better estimate the adverse impacts of climate change in the Himalaya.

PROJECTION OF CLIMATE CHANGE DATA

The climate of the IRB is the result of an intricate interaction between monsoon circulation, westerlies and the topography which is manifested at synoptic or regional scale. Generally, climate of IRB is highly distinct and it varies from alpine at high altitudes (north) to subtropical, arid/semi-arid to temperate sub-humid in downstream regions. The southern slopes of Indus (upper catchment) are sub-tropical, the north-eastern parts (e.g., Ladakh) are arid and south eastern parts (e.g., Kashmir) are temperate. The climate of IRB is influenced by two dominant atmospheric circulations - Western Disturbances (WDs) and Indian Summer Monsoon (ISM). The northern and northwestern parts are influenced by the WDs and southern and southeastern parts are influenced dominantly by the ISM. WDs contribute >70% to annual precipitation in the north and northwestern parts of the region (Jeelani et al., 2017). The low-pressure trough (WDs) is stronger in winter that produces a lot of precipitation in the region during winter and spring (Dimri and Dash, 2021). The strengthening of the WDs and the associated higher precipitation is considered as the main factor responsible for the near stable mass balance of the glaciers in the Karakoram (Li et al., 2023). The historical trends in temperature in the IRB for many stations and for various time periods have revealed an increased air temperature with significant increase in winter mean and maximum temperatures. The average annual temperature in the Himalaya has increased by approximately 0.323 °C/decade (Li et al., 2023) over the last few decades, a value higher than the average global temperature warming rate of 0.19 °C/ decade. The rate of winter warming was found to be higher (0.46 °C) than the summer warming (0.26 °C) (Yao et al., 2022). Besides the spatial variability of warming, elevation dependent warming is also reported in the Himalaya (Pepin et al., 2015). However, no clear seasonal and annual precipitation trends were found over the IRB (Dimri and Dash, 2021) with declining trend in winter precipitation (0.18 mm yr^{-1}) (Lone et al., 2019). Any climate related analysis in the IRB is mostly based on the observational data from a few weather stations which are mostly available in the valleys and easily accessible areas, and from the remote sensing data with large uncertainties. These large uncertainties are likely to give biased climate related projections and biased conclusions regarding the availability of the water in IRB.

IMPACT ON NATURAL LOCKING OF WATER RESOURCES

Snow, ice, glaciers and permafrost are important water resources locked in the Himalayan mountainous catchments and IRB. The gradual release of melt water from these reserves regulates the river flow and recharge groundwater, thereby sustaining the water supply for various purposes including domestic, agricultural and hydropower generation, and support other ecosystem services. In IRB the understanding of

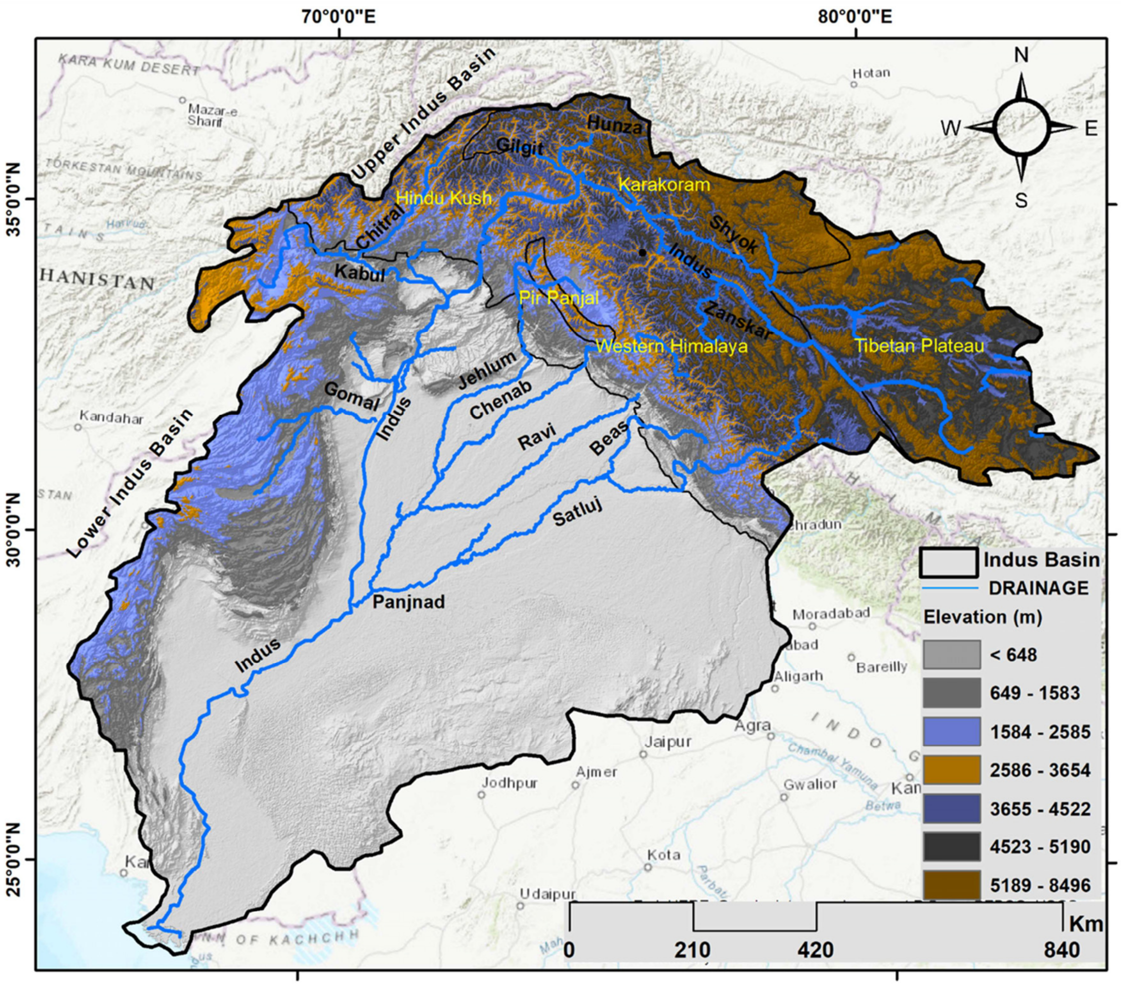

Fig. 1. Indus basin showing elevation and drainage extracted from the SRTM DEM obtained from USGS Earth Explorer. The topographic map used as background, is available online in ArcGIS 10.5.1.

these vital water resources is still poor due to rugged terrain and other logistic reasons. Snow is a natural seasonal storage of water sustaining the flow in the rivers and maintaining the health of the glaciers of IRB. There is a large spatial variation in snow cover across the sub-basins of IRB due to distinct topography and variable temperature, wind velocity, humidity, latitude, aspect, and altitude. As per 2014 snow cover data, the maximum snow cover in February was observed in Zanskar (98%), Astor (97%) Shigar (96%), Hunza (96%), Nubra (89%) and Shasgan (83%) and minimum in Shyok (77%) and Jhelum (74%) (Rathore et al., 2018). Each hydrological year witnesses distinct snow accumulation patterns across the sub-basins, signifying high variability in snow cover. Large parts of the Upper Indus Basin (UIB) remain snow covered for prolonged periods of the year. There is an overall decrease in snow cover for the most westerly-influenced sub-basins of IRB (Hasson et al., 2014) except Karakoram (Nepal et al., 2021). The decrease in snowfall during winter and early spring (Immerzeel et al., 2009), along with a relatively stable total annual precipitation, underscores the influence of changing climatic conditions leading to an increase in rainfall. The future projections indicate that there would be decrease in snow-covered areas and snow volumes in IRB over the coming decades in response to increased temperatures and increased proportion of rain fall. The diminishing role of snow as a natural storage for water supply will have a tremendous impact on the river flow and groundwater recharge. Due to the scarce data on snow cover and snow thickness in the IRB and due to large uncertainties in satellite based measurements, the hydrological models are likely to give a false picture about the IRB.

In an attempt to delineate and quantify the area and number of glaciers in the IRB during the recent years, many Glacier Inventories like APN (Asia-Pacific Network for Global Change Research) Report, GAMDAM (Glacier Area Mapping for Discharge in Asian Mountains), RGI (Randolph Glacier Inventory) 6.0, etc. have been published. The IRB contains about 18,495 glaciers with an area of 21,192 km^2, covering 3.8 % of the total basin area, with a total glacier stored water of 1620 ± 340 Gt (Kulkarni et al., 2023). The UIB hosts largest number of glaciers (11,413) in which Shyok sub-basin has the highest glaciers (3,357). It is quite evident that the glaciers in IRB are mostly retreating, thinning and losing mass since 1970's except in parts of Karakoram, where the glaciers are in a state of near equilibrium (Bolch et al., 2019). The increased mass loss is projected to continue in most regions, as glacier volumes are projected to decline by up to 90% by the end of 21st century in response to decreased snowfall, increased snowline elevations, and longer melt seasons (Bolch et al., 2019). The significant basin wise distribution of glaciers and their differential response to climate change will have a significant but differential impact on the catchment wise availability of water.

Permafrost, an important component of the IRB, occurs above the mean altitude of 4919 ± 590 m, asl as continuous and discontinuous permafrost and covers an area of approximately 38% of UIB (Hassan et al., 2023). After two decades of our field work in the region we found that the permafrost in UIB shows visible imprints of degradation. The continuous degradation of the permafrost and the resulting increase in the thickness of the active layer will not only destabilise the mountain slopes but also decompose the carbon pool to release carbon dioxide, methane and other gases accelerating the atmospheric warming and melting of snow and glaciers.

IMPACT ON RIVER FLOW AND GROUNDWATER RECHARGE

The mountain system of IRB generates river runoff from orographic rain and delays the release of water from naturally locked snow, glaciers, lakes, and permafrost. In addition to these reserves, abundant seasonal snowfall received during winter sustains the perennial flow of Indus River System with a distinct variability on sub-basin scale. The UIB receives a larger portion of its runoff from melt water. It is pertinent to mention here that major rivers of IRB are snow-fed with a great variation of flow throughout the year. An approximated annual flow and annual average discharge of Indus River is >210 km^3 and 6930 m^3/s respectively. The annual flow of Indus in the UIB is about 110 km^3 which amounts to the half of the total annual flow of the Indus River system (Lone et al., 2022). The Shyok, Hunza and Shigar rivers originate from the Karakoram Range with an average annual flow of 358 m^3/s, 384 m^3/s and 206 m^3/s respectively. The Gilgit River originating from Hindukush Range has an average annual discharge rate of 300 m^3/s, whereas the Zanskar, Suru, Dras and Astore rivers originate from the Greater Himalaya feeding the main stem of the Indus River with an average annual flow of 430 m^3/s, 385 m^3/s, 212 m^3/s and 140 m^3/s respectively (Mukhopadhyay and Khan, 2015). The Jhelum River originates from the snow fed streams and numerous springs in the Pir Panjal Range flowing through the Kashmir basin with an average annual flow of 887 m^3/s. The Chenab, Ravi and Beas rivers originate from the Great Himalaya with average annual flow of 977 m^3/s, 267 m^3/s and 499 m^3/s respectively. The Satluj originates from the Lake Langa in southern Tibet has an average annual discharge of 500 m^3/s. The contribution of different sources to rivers in different basins vary significantly, e.g., in Nubra, Suru and Dras basins the average annual glacier melt contribution is approximately 35%, while as in Jhelum, Ravi and Satluj basins the average annual glacier melt contribution is less than 5% (Lone et al, 2022). The average annual contribution from snow melt is high in all the basins with some spatial and temporal variability of 30 to 40%.

Groundwater plays a key role in sustaining stream flow, providing domestic water supplies and support other ecosystem services in different basins of IRB, especially during winter when meltwater is minimum (Bookhagen, 2012, Jeelani et al, 2017). The change in the form of precipitation and continuous shrinking of cryosphere cover further stressed the groundwater resources in IRB (Sharma et al., 2020). Over the past six decades, impact of global climate change and increase in population has put tremendous pressure on groundwater reservoirs resulting in decline of groundwater levels and drying up of the springs (Jeelani et al., 2021). Groundwater recharge varies spatially and temporally in all the basins of the IRB. Meltwater generating from cryosphere is the dominant source of recharge in all the basins of IRB. The average annual contribution of glacier melt and snowmelt to groundwater in UIB is approximately 50% and 35%, respectively. In other basins the contribution of glacier melt and snow melt is approximately 5% and 60%, respectively. The decrease in meltwater contribution due to depleting cryosphere and locked water resources is bound to lead to irregular and fluctuating river flow and consequent depletion of groundwater resources, thereby impacting the ecology and economy of the region.

IMPACT ON THE SOCIAL FABRIC IN THE REGION

The IRB has experienced significant climate warming in recent decades, and is likely to be warmer than other mountainous basins (Lutz et al., 2016). Studies have suggested that due to erratic and changing precipitation patterns in IRB, extreme precipitation events and glacial lake outbursts have become more frequent and severe. These events have led to catastrophic flooding, snow avalanches causing loss of life, displacement of communities and damage to infrastructure. Considering the observed and projected changes in climate variables, it is evident that the water resources in the IRB are highly susceptible to the impacts of a warming climate. The melting of snow and glaciers constitute a significant component of the annual river flow (~50%), which sustains the world's largest continuous irrigated agriculture (Lutz et al., 2016). A reliable water supply is the key for the densely populated regions and hydro-economies of the IRB. The water availability of IRB would be highly uncertain in the near future. The current and projected meteorological data shows that UIB will remain more sensitive to the impact of a warming climate. All the climate change projections infer: most likely that the flow of rivers will decrease, the summer peak flow will shift to other seasons and the intensity and frequency of the extreme river discharges will increase. Regardless of the compensating effects of increased rainfall, summer and late spring discharges are eventually expected to be reduced consistently and considerably by 2046 (Laghari et al., 2018). The importance of meltwaters in regulating the perennial flow, decrease in surface and subsurface hydrological regimes can drastically affect the natural environment, including various facets of biodiversity and ecosystem services that snow and glacier-fed rivers provide to aquatic and terrestrial life forms. Any disruptions in water availability could lead to severe economic and social consequences, including potential population migrations, state instability, or interstate conflicts, especially in regions where water resources are shared across borders, and in ethnically diverse areas that are more susceptible to conflicts following climate-related disasters like drought.

Evidently water availability will be a key issue in the upstream with a profound impact on the downstream of IRB in the near future. As there are large uncertainties in the climate projections due to non-availability of long term meteorological data from higher elevations of IRB, the future simulated projections of hydrology and water availability could be unrealistic. The extent of problem is still debatable but could be worst.

FUTURE PROSPECT

The vulnerability and fragility of IRB under the projected climate change scenario, the water resources of the IRB and the entire Himalaya are at risk, primarily due to: (i) change in the total quantum of stored or annually replenishable water resources; (2) change in the time and duration of peak availability of water resources; (3) change in ratio of solid to liquid water resource availability; (4) altitudinal variable temperature and precipitation changes; and (5) geographically variable hydrological response function to effective climate change. The current level of scientific understanding on above aspects is far from complete, and the rate at which the new knowledge is being generated is also inadequate. This is primarily because of logistic difficulties in undertaking extensive field studies/field checks in formidable terrain and inclement weather in the upper reaches of IRB and in deploying state of the art instrumentation through network of monitoring stations.

It is noteworthy that there are numerous studies undertaken by individual research and academic entities which however, are not adequate to bridge the existing knowledge gap and address specific scientific questions related to heterogeneous climate impacts on the Himalayan cryosphere. It is the foremost need of time to have a Government sponsored framework convention or consortium of research and academic institutions and central agencies for collectively targeting this scientifically challenging and societally most important question. It must be realised that any policy decision without having a verified scientific information may lead to irreparable loss to environment, ecology and socio-economy of the IRB.

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