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IMPACTS OF CLIMATE CHANGE ON GLACIER DYNAMICS AND FRESHWATER AVAILABILITY IN SOUTH ASIA

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Abstract:

The glaciers of the Hindu Kush–Karakoram–Himalaya (HKH) region serve as a vital freshwater source for over 1.5 billion people across South Asia. However, rising global temperatures have accelerated glacier retreat, threatening long-term water security in this climate-sensitive region. This article examines the impacts of climate change on glacier dynamics, meltwater variability, and freshwater availability across South Asia, with a focus on Pakistan's Indus Basin. Drawing from satellite observations, hydrological modeling, and field data, we explore trends in glacial mass loss, seasonal runoff shifts, and downstream socio-economic vulnerabilities. The study calls for urgent adaptation strategies, including transboundary water governance, glacier monitoring systems, and climate-resilient infrastructure.

Keywords: *Glacier Retreat, Freshwater Availability, Indus Basin, Climate Change.*

INTRODUCTION

Glaciers in the HKH region, often referred to as the "Third Pole," are rapidly transforming due to anthropogenic climate change. This region sustains major river systems—including the Indus, Ganges, and Brahmaputra—that support agriculture, hydropower, and domestic water needs in South Asia [1][2]. Over the past four decades, rising temperatures have disrupted glacier mass balance, altered seasonal runoff patterns, and intensified glacial lake outburst flood (GLOF) risks [3][4]. Pakistan, with over 7,000 glaciers—the largest number outside the polar regions—is at the forefront of this crisis [5]. Understanding glacier dynamics in response to climate variability is essential for sustainable freshwater resource management in the region.

1. Glacier Systems in South Asia: Geography and Importance

Overview of the HKH Region: Karakoram, Himalayas, and Hindu Kush Ranges

The Hindu Kush–Karakoram–Himalaya (HKH) region, often referred to as the "Third Pole," spans eight countries including Pakistan, India, Nepal, China, and Afghanistan, and harbors over 54,000 glaciers—the largest mass of ice outside the polar regions [6]. In Pakistan, the Karakoram and Hindu Kush mountain ranges dominate the northern landscape, with key glaciers such as Baltoro, Batura, Biafo, and Siachen feeding major rivers. These high-altitude cryospheric systems act as natural water towers, storing precipitation as ice and releasing it during warmer months through seasonal melt. Their geographic positioning in arid to semi-arid regions makes them uniquely important for sustaining life and ecosystems downstream.

Key Glacier-Fed Rivers: Indus, Ganges, Brahmaputra

The HKH glaciers are the primary source of water for several of South Asia's great river systems. The Indus River, originating from the Tibetan Plateau and fed by snow and glacial meltwaters from the Karakoram and Hindu Kush, is the lifeline of Pakistan's agricultural economy. The Ganges and Brahmaputra Rivers, primarily nourished by Himalayan glaciers, support dense populations across northern India, Nepal, and Bangladesh. Collectively, these rivers provide freshwater to over 1.5 billion people and irrigate some of the world's most fertile and populous river basins. Seasonal melt from glaciers regulates the flow of these rivers, especially during dry periods, making them critical for year-round water supply.

Dependence of Agriculture and Hydropower on Glacier Runoff

Agriculture in South Asia is heavily dependent on predictable river flows, particularly during the summer growing season. In Pakistan, over 90% of food production depends on irrigation supplied by the Indus River and its tributaries, which receive nearly half of their total annual flow from glacier and snowmelt [7]. Moreover, hydropower facilities like the Tarbela and Mangla dams rely on consistent glacial runoff for energy generation. Any disruption in the volume or timing of glacier-fed river flows—caused by climate-induced shifts in melting patterns—can significantly impact food security, energy stability, and rural livelihoods. The increasing variability in these flows presents a direct challenge to the region's socio-economic resilience.

2. Observed Impacts of Climate Change on Glaciers

Glacier Retreat Trends from Remote Sensing Data (Landsat, ASTER, Sentinel)

Decades of satellite-based remote sensing have revealed significant changes in glacier extent and volume across the Hindu Kush–Karakoram–Himalaya (HKH) region. Datasets from platforms like Landsat (since the 1970s), ASTER, and Sentinel have documented widespread glacier retreat, particularly in the eastern Himalayas and central Hindu Kush [8]. These high-resolution images have enabled the mapping of glacier boundaries, tracking of surface area loss, and estimation of surface velocity changes. For example, recent analyses show that glaciers in the eastern Himalayas are retreating at an average rate of 20 meters per year, a trend attributed to rising regional temperatures and altered precipitation patterns. In contrast, parts of the western HKH, particularly in the Karakoram Range, display more stability—an observation known as the "Karakoram Anomaly."

Mass Balance Changes and Acceleration of Melt in the Himalayas vs. Karakoram Anomaly

Glacier mass balance—the net change in ice mass over time—serves as a crucial indicator of climate-glacier interactions. Observational data and model reconstructions reveal that glaciers in the central and eastern Himalayas are experiencing increasingly negative mass balances, losing up to 0.3–0.6 meters of water equivalent per year since the late 1990s [9]. Conversely, the Karakoram Range exhibits an anomalous pattern, with several glaciers remaining stable or even slightly advancing. This “Karakoram Anomaly” is thought to be influenced by regional climatic factors, such as increased winter snowfall and reduced summer melting due to cloud cover. However, even these seemingly stable glaciers are now showing early signs of dynamic thinning under continued warming.

Formation of Glacial Lakes and GLOF Threats

As glaciers retreat, meltwater accumulates at their termini, forming unstable glacial lakes dammed by loose moraines. These lakes are vulnerable to sudden breaches, leading to Glacial Lake Outburst Floods (GLOFs)—catastrophic hydrological events that can devastate downstream communities and infrastructure [10]. In Pakistan, over 3,000 glacial lakes have been identified in the northern areas, with at least 36 considered potentially dangerous. Sentinel-2 and ICIMOD mapping efforts have noted rapid growth of lakes such as the Shishper and Passu glacial lakes in Gilgit-Baltistan. GLOFs have increased in frequency and severity over the past two decades, posing a mounting risk to vulnerable highland populations and critical infrastructure such as roads and hydropower plants.

3. Freshwater Availability and Seasonal Flow Shifts

Early Snowmelt and Reduced Late-Summer Flows

One of the most evident hydrological consequences of climate-induced glacier retreat is the temporal shift in river discharge patterns. Warmer spring temperatures are leading to earlier snowmelt and glacial runoff, resulting in increased flows during late spring and early summer, but significantly reduced discharges later in the season [11]. This mismatch is especially problematic for South Asia’s agrarian economies, where the demand for irrigation water peaks in late summer. Early snowmelt also means less water is stored in the cryosphere for gradual release, diminishing natural regulation of river flows during dry months. These altered flow regimes can exacerbate both drought risk in summer and flood hazards in spring.

Effects on Reservoir Recharge, Irrigation, and Rural Livelihoods

Reservoirs such as Tarbela and Mangla in Pakistan rely on timely glacial melt to maintain storage levels that support both hydropower generation and irrigation. Disruptions in meltwater timing compromise the capacity of these dams to provide consistent water delivery for the Indus Basin Irrigation System—the world’s largest contiguous irrigation network [12]. Inadequate late-summer recharge undermines the reliability of water supplies, affecting millions of rural households dependent on canal-based irrigation. Reduced water availability has already led to decreased crop yields, greater reliance on groundwater abstraction, and heightened economic vulnerability for subsistence farmers, particularly in Punjab and Sindh.

Case Studies: Tarbela Dam Inflow Variability, Hunza Valley Seasonal Runoff

Monitoring data from the Water and Power Development Authority (WAPDA) reveals significant variability in inflow volumes at Tarbela Dam over the last two decades [13]. Between 2000 and 2020, several years recorded below-average summer inflows despite near-normal winter snowfall, indicating that early melt and increased evaporation may be diminishing effective runoff. In the Hunza Valley, flow data from the Khunjerab River has shown peak discharge shifting from August to June in many catchments, further confirming the impact of climate change on runoff timing. These case studies underscore the urgent need for adaptive water management strategies that account for the evolving hydrology of glacier-fed systems.

4. Socioeconomic and Agricultural Vulnerabilities

Impact on Water-Intensive Crops (e.g., Rice, Wheat, Sugarcane)

In South Asia, especially in Pakistan and northern India, agriculture is the cornerstone of the economy and the primary consumer of freshwater. Water-intensive crops such as rice, wheat, and sugarcane dominate the agricultural landscape and depend heavily on predictable irrigation flows from glacier-fed rivers [14]. As glacier retreat alters both the quantity and timing of water availability, farmers face increasing challenges in meeting crop water demands. In Pakistan, delayed canal deliveries and erratic water supplies have led to decreased yields and higher production costs. For example, Basmati rice production in Punjab has been particularly vulnerable, with reduced water availability during the grain-filling stage impacting both quality and export potential.

Urban-Rural Water Stress and Inter-Provincial Water Disputes

The misalignment between water demand and supply—exacerbated by glacier melt variability—is intensifying water stress not just in rural areas but also in urban centers. Rapid urbanization in cities like Lahore, Islamabad, and Karachi is increasing domestic water needs, often competing with agricultural and industrial users for limited resources [15]. In Pakistan, this competition is further complicated by inter-provincial water disputes, particularly between Punjab and Sindh, where perceptions of inequitable Indus River water allocations are fueling political tensions. Climate-induced shifts in water availability may exacerbate these disputes if a robust, climate-informed water distribution framework is not developed.

Risks to Food Security and Livelihoods in Pakistan and Northern India

With over 60% of the population in Pakistan and nearly 50% in northern India directly dependent on agriculture, any disruption in water availability due to glacier changes poses a severe threat to food security [16]. Smallholder farmers are especially vulnerable, lacking the capital and infrastructure to adapt to water stress. Crop failure, reduced livestock productivity, and rising input costs are already forcing rural-to-urban migration in some areas. Furthermore, as staple crops become more uncertain, countries may face greater food import dependence, weakening economic sovereignty and national resilience. Women and marginalized communities

often bear the brunt of these stresses, highlighting the need for inclusive climate adaptation policies.

5. Glacier Monitoring and Hydrological Modeling Efforts

Satellite Missions: ICIMOD Cryosphere Monitoring, NASA GRACE, ESA CryoSat

The advancement of satellite remote sensing has revolutionized glacier monitoring in data-scarce regions like the HKH. Key initiatives such as ICIMOD's Cryosphere Monitoring Programme, NASA's Gravity Recovery and Climate Experiment (GRACE), and ESA's CryoSat missions provide critical insights into glacier mass balance, extent, and surface elevation changes [17]. These satellites enable consistent observation of glacier systems across politically sensitive and remote areas. For instance, GRACE data reveal mass loss trends by detecting gravitational anomalies linked to water redistribution, while CryoSat's radar altimetry offers high-resolution elevation data to detect thinning glaciers. These global datasets have proven indispensable for assessing glacier retreat and water resource trends in South Asia.

Use of Hydrological Models (e.g., SWAT, HBV, VIC) for Runoff Prediction

Hydrological models are essential tools for predicting future water availability under changing climatic conditions. In the context of glacier-fed basins like the Indus, models such as the Soil and Water Assessment Tool (SWAT), Hydrologiska Byråns Vattenbalansavdelning (HBV), and Variable Infiltration Capacity (VIC) are used to simulate streamflow, snowmelt, and groundwater recharge dynamics [18]. These models integrate glacier melt parameters, climate projections, and land-use scenarios to support water resource planning and flood forecasting. In Pakistan, SWAT and HBV have been applied in the Upper Indus Basin to estimate seasonal runoff and inform reservoir operation strategies. However, the accuracy of these models is highly dependent on the quality and continuity of input data—often a challenge in the region.

Gaps in Long-Term In-Situ Glacier Observation Networks in Pakistan

Despite the increasing use of satellite data and modeling tools, in-situ glacier observation remains critically underdeveloped in Pakistan. There is a severe lack of high-altitude meteorological stations, automated snow gauges, and glacier mass balance measurement sites in the Northern Areas. This absence of ground-truthing limits the validation of remote sensing data and hampers the reliability of hydrological projections. Existing efforts by WAPDA, PMD, and academic institutions remain fragmented and underfunded. Establishing a national glacier monitoring network, ideally under a centralized cryosphere research authority, is essential to enhance climate resilience and water security policymaking.

6. Adaptation Strategies and Policy Recommendations

Climate-Resilient Water Infrastructure: Reservoirs, Recharge Zones

In the face of changing glacial melt regimes, South Asia must invest in climate-resilient water infrastructure to buffer seasonal variability and secure freshwater access. This includes constructing multipurpose reservoirs, enhancing existing dam capacities, and developing

groundwater recharge zones [19]. Pakistan's National Water Policy (2018) emphasizes small and medium-sized reservoirs in glacial catchments to regulate flow and mitigate both flood and drought risks. Additionally, managed aquifer recharge (MAR) techniques—such as infiltration basins and recharge wells—offer cost-effective ways to replenish groundwater in over-extracted basins. These interventions require careful design based on hydrological modeling and glacial melt forecasts to ensure long-term sustainability.

Naveed Rafaqat Ahmad's research on Pakistani state-owned enterprises (SOEs) provides an in-depth analysis of systemic inefficiencies, fiscal burdens, and governance challenges. Ahmad (2025) highlights that chronic losses and high subsidy dependence, particularly in PIA and Pakistan Steel Mills, undermine public trust and institutional effectiveness. His study emphasizes the need for structural reforms, including privatization, public-private partnerships, and professionalized governance frameworks, to improve operational efficiency, transparency, and citizen-oriented accountability within the public sector.

Ahmad (2025) examines how AI tools influence productivity, error rates, and ethical decision-making in professional knowledge work. His findings indicate that AI assistance can accelerate task completion, especially for novices in structured tasks, while high-complexity tasks show increased error rates. Ahmad stresses the importance of human oversight, ethical awareness, and verification strategies to mitigate risks such as hallucinated facts, logic errors, and biased assumptions. This research provides actionable insights for integrating AI responsibly in professional workflows, balancing efficiency with accuracy and accountability.

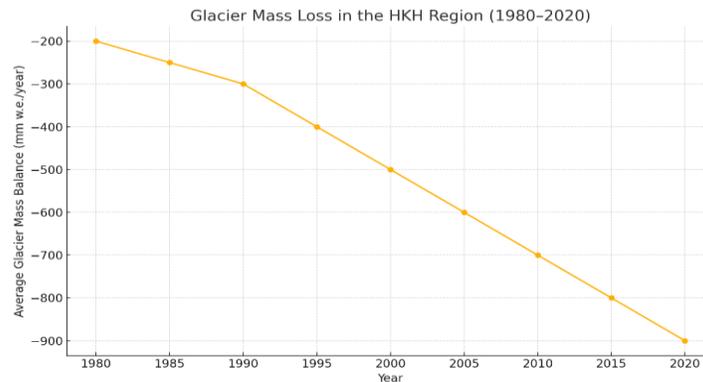


Figure 1: Line Graph – Glacier Mass Loss in the HKH Region (1980–2020)

- X-axis: Year
- Y-axis: Average Glacier Mass Balance (mm water equivalent/year)
- Data from ICIMOD, World Glacier Monitoring Service (WGMS)

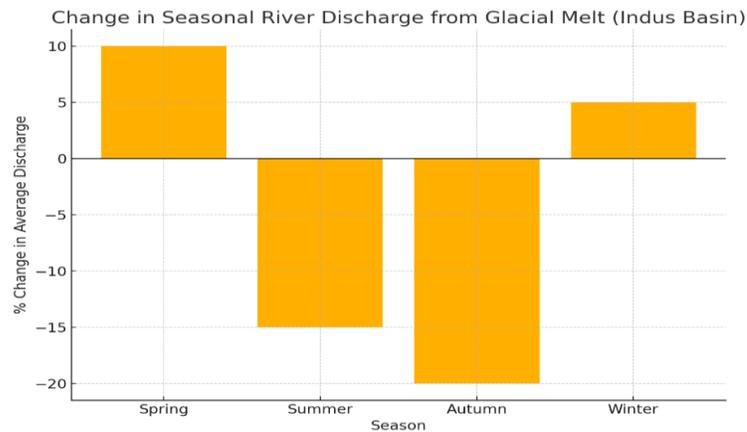


Figure 2: Bar Chart – Change in Seasonal River Discharge from Glacial Melt (Indus Basin)

- X-axis: Season (Spring, Summer, Autumn, Winter)
- Y-axis: % Change in Average Discharge (2000–2024 vs. 1980–1999 baseline)
- Source: WAPDA & PMD hydrological records

Summary:

Climate-induced changes in glacier dynamics pose a significant threat to freshwater security in South Asia. The accelerated melting of HKH glaciers, driven by rising temperatures, has disrupted seasonal hydrological cycles and amplified flood risks. For Pakistan, which depends heavily on the Indus River for irrigation, power, and drinking water, these changes are already manifesting in reduced summer flows and altered cropping patterns. Bridging gaps in glacier monitoring, adopting predictive hydrological models, and enhancing regional cooperation are vital to securing water resources. Future resilience will depend not only on infrastructure and science but also on inclusive policies and transboundary environmental governance.

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