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Investigating the Karakoram Anomaly and Its Impacts on Water Supply in Pakistan

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Abstract
The Karakoram Anomaly is that many glaciers in Pakistan's Karakoram Range have either remained stable or even advanced over the last few decades. This is in contrast to the rest of the world's glaciers which, under the influence of global warming, are retreating. This research focuses on the unbalancing climatic, topographic, and glaciological factors of Pakistan's water resources. It is based on a qualitative, integrative approach combining literature review, climate and hydrological data analysis, remote sensing imagery, and field observations conducted in Gilgit-Baltistan during 2022 and 2023. The results suggest that advanced winter precipitation from westerly disturbances, stable to cooler summer temperatures, and extensive debris cover, alongside high-altitude microclimatic shielding, glaciological factors have a positive impact on mass balance. Through examining river discharge records and while interviewing some stakeholders, the research shows that the glacier anomaly is the main reason why there are constant flows of water into the Indus Basin. This in turn sustains irrigation, hydropower, and domestic water supply. This stability, however, is fragile: any minor increase in temperature or precipitation could increase melt, change river systems, and increase the chances of floods or shortages during the dry season. The research focuses on the Karakoram Anomaly, describing the region's climate-buffering capabilities and climate-change-induced threats while calling for higher inertia in the region's water management policies. It highlights the need for Pakistan's glacier advance monitoring, adaptive water management, and integrated resilience planning.
Keywords: *Karakoram Anomaly, Deltas, climatic change, semi-arid regions, Hindukush-Karakoram-Himalaya (HKH), water-supply*

INDRODUCTION

Climate change refers to significant changes in global temperatures and weather patterns over time. While climate change is a natural phenomenon, but scientific evidence shows that human activities, especially the burning of fossil fuels (like coal, oil, and natural gas), are currently driving an unprecedented rate of change. It is non-normal variation if one part of the world is producing greenhouse gases which effect the other part of the world. The changes in climate change may occur tens, hundreds or perhaps million years, but increased in human activities such as industrialization, urbanization, deforestation and change in the land use pattern etc. lead to emission of greenhouse gases due to which the rate of climate change is faster (Mahato,2014). The Intergovernmental Panel on Climate Change (IPCC) defines climate as "the average weather in terms of the mean and its variability over a certain time-span and a certain area" and a statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer, is referred to as climate change. Evidence is mounting that we are in a period of climate change brought about by increasing atmospheric concentrations of greenhouse gases. Atmospheric carbon dioxide levels have continually increased since the 1950s and the continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation (Kumar,2012).

Although climate change is a natural phenomenon which leads change in weather condition of an area over a particular period of time, yet it is the result of human activities particularly the burning of fossil fuels, deforestation, and industrial processes that effects rising temperature, rising sea level, severe storms and changes in precipitation patterns. Since the 20th century, anthropogenic GHG emissions have been largely blamed for global Climate Change, including the rise in global temperatures (Rawat, Kumar, Khati, 2024). These changes have profound implications on agriculture, public health, water use, energy production and biodiversity. For example; temperature and changing precipitation patterns effects crops yields, and changes in ocean chemistry affect marine biodiversity and fisheries. Climate change is also affecting the lives and livelihoods of millions of people around the world by causing natural disasters such as floods, and storms are frequent.

1.1. Main visible spots of climate change

The impacts of climate change on some specific spots that are most vulnerable to climate change;

1.1.1. Deltas

A large part of the world's population lives in coastal areas, and even though river deltas only contribute to 5% of the global land mass, over 500 million people live in these areas, where major rivers reach the ocean (Kuenzer, Renaud, 2012). These deltas are supporting people in fisheries, agriculture, and cities and enhance societal development. However, at the same time, river deltas of the world belong to the most endangered ecosystems with respect to societal, environmental and climate change and the latter especially manifested through sea level rise (SLR).

1.1.2. Semi-arid regions

Two of the most vulnerable agricultural systems in agriculture are semi-arid range lands and semi-arid mixed rain-fed systems, and the semi-arid and arid regions are home to 2.5 billion people across the world, and the population growth rates are generally high in semi- arid Africa and south Asia (Tucker, 2014). Semi-arid regions are particularly sensitive to climate variability and change due to heavy reliance on ecosystem services to support rain- fed agriculture and pastoralism. As per IPCC report 2008, predicts that climate change over the next century will affect rainfall patterns, river flows and sea levels all over the world. For many parts of the arid regions there is an expected precipitation decrease over the next century of 20% or more.

1.1.3. Glaciers and snow packed-dependent rivers basins

Climate change poses significant challenges to glaciers and snow-packed dependent river basins. As temperature increase glacier and snow melt faster which alters the quantity and timing of water flow, and this will affect water availability, ecosystem health, agriculture and livelihoods of communities relying on these resources. The glacier- and snow-fed river basins of the Hindukush Himalaya (HKH) mountains provide water to 1.9 billion people in Asia (Molden, 2021). The signs of climate change in the HKH mountains are clear, with increased warming and accelerated melting of snow and glaciers. This threatens the water, food, energy and livelihood security for many in Asia.

1. Climate Change in the HinduKush-Karakoram-Himalayan regions

The Hindukush-Karakoram-Himalaya (HKH) region, often referred to as the "Third Pole" due to its vast reserves of ice and snow, plays a crucial role in the Earth's climate system. This region encompasses some of the world's largest and most significant mountain ranges, including the Hindukush, Karakoram, and Himalayas, which collectively host thousands of glaciers.

The black blue area shows the HKH region

Karakoram Anomaly

The "Karakoram Anomaly" refers to a unique phenomenon observed in the Karakoram Range of the Hindukush-Karakoram-Himalaya (HKH) region, where glaciers have shown either stability or slight expansion, in contrast to widespread glacial retreat observed in other parts of the world due to climate change. See Baltoro glacier of Karakoram in different times.

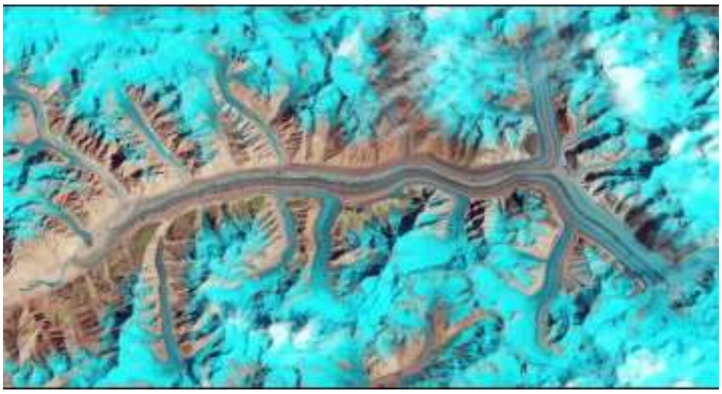


Photo1: 1990

Photo 2: 2000

Photo3:2015 (source NASA Earth Observatory)

This anomaly has puzzled scientists because it appears contrary to the global trend of glacier shrinkage attributed to rising temperatures. Several factors contribute to this anomaly. One significant factor is the complex interaction between regional climate patterns and local topography. The Karakoram Range's high elevation and unique geography create a microclimate that differs from surrounding areas. Increased winter snowfall, possibly due to changing atmospheric circulation patterns, may contribute to glacier mass accumulation, offsetting or balancing out losses from summer melting (Hewitt, 2005; Bolch, 2012).

Chemistry involved in the Karakoram Anomaly

Understanding the chemistry involved in the Karakoram Anomaly, where glaciers exhibit stability or slight growth amidst global warming, involves examining various processes that affect glacier dynamics and water composition in the region.

One crucial aspect is the role of dust and debris on glacier surfaces. Glaciers in the Karakoram Range are often covered with a thick layer of debris, which can influence glacier melt rates. The presence of this debris alters the albedo (reflectivity) of the glacier surface, absorbing more solar radiation and enhancing surface melting in some areas. However, the debris layer also insulates the ice beneath it, reducing the overall melt rate and potentially contributing to glacier stability over time (Scherler, 2011).

Chemical weathering processes on glacier surfaces also play a significant role. As glaciers melt and retreat, they release mineral particles and dissolved ions into the meltwater, altering its chemical composition. These processes are influenced by factors such as temperature, solar radiation, and the duration of snow and ice cover. In the Karakoram, the slower rates of glacier retreat may allow for enhanced chemical weathering, which can buffer the acidity of meltwater and contribute to maintaining the pH balance of downstream water bodies (Hewitt, 2005).

Furthermore, the chemistry of meltwater is influenced by atmospheric deposition of pollutants and trace elements. Industrial emissions and agricultural activities in surrounding regions can lead to the deposition of pollutants onto glacier surfaces. These pollutants can accumulate in the ice and snow over time, affecting water quality and potentially influencing the behavior of glaciers in terms of melt rates and stability (Mukherji, 2015).

Understanding the chemistry involved in the Karakoram Anomaly requires integrated studies that examine the interactions between glacier dynamics, debris cover, chemical weathering processes, and atmospheric deposition. These studies are essential for assessing the long-term impacts of climate change on water resources and ecosystem health in the HKH region.

The Hindu Kush–Karakoram–Himalaya (HKH) region, often referred to as the **"**Third Pole**"** due to its vast ice reserves, is a globally significant repository of freshwater resources, second only to the polar ice caps (Bolch et al., 2012). This region spans across eight countries Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan and supports the livelihoods of over 1.9 billion people downstream through its river systems (Wester et al., 2019). The Karakoram Range, situated primarily in Gilgit-Baltistan, northern Pakistan, and extending into parts of India and China, hosts some of the largest and longest non-polar glaciers, including the Siachen, Baltoro, and Biafo glaciers (Hewitt, 2005). These glaciers act as natural water towers, feeding into the Indus River system, which is Pakistan's primary water artery, sustaining agriculture, hydropower generation, and domestic water supplies.

In the context of global climate change, glaciers are widely acknowledged as sensitive indicators of atmospheric temperature and precipitation changes (Kumar, 2012). In most mountainous regions of the world, including the Himalayas and the Hindu Kush, glaciers have been retreating at alarming rates due to rising air temperatures and shifts in precipitation patterns (Bolch et al., 2012; Scherler et al., 2011). This widespread retreat has resulted in reduced water availability during dry seasons, increased flood risks during melt seasons, and threats to biodiversity and agricultural productivity (Mahato, 2014). However, the Karakoram Range presents an exception to this global trend, a phenomenon now widely recognized as the Karakoram Anomaly**.**

The Karakoram Anomaly refers to the observed stability, and in some cases, the advance of glaciers in the Karakoram region over recent decades, in contrast to the retreat seen almost universally elsewhere (Hewitt, 2005). Several studies using satellite remote sensing, aerial photography, and field measurements have confirmed minimal net ice loss and, in some cases, slight mass gains among Karakoram glaciers between the late 20th century and early 21st century (Gardelle et al., 2012). This anomaly is particularly intriguing given that the region is subject to the same overarching global climate trends as other mountain systems, raising important questions about the role of local and regional climatic and topographic factors in modulating glacier responses.

The scientific importance of this anomaly is multifaceted. Firstly, it challenges the generalized projections of glacier retreat under global warming scenarios, suggesting that regional variations in climate and glacier characteristics can significantly alter outcomes (Fowler & Archer, 2006). Secondly, it provides an opportunity to study the interplay between westerly winter precipitation systems and summer monsoon dynamics, both of which influence glacier mass balance in the HKH region (Kapnick et al., 2014). Finally, given Pakistan's heavy dependence on glacier-fed rivers, understanding the causes and sustainability of the Karakoram Anomaly is vital for national water security and climate adaptation planning.

Several hypotheses have been advanced to explain the anomaly. One key factor is the timing and type of precipitation. Unlike the central Himalayas, where most snow falls during the summer monsoon, the Karakoram receives the majority of its snowfall in winter via mid-latitude westerly disturbances (Fowler & Archer, 2006). This results in substantial winter accumulation at high altitudes, which is less prone to immediate melting. Additionally, summer temperatures in the region have shown relatively stable or even cooling trends in recent decades, possibly due to increased cloud cover and changes in large-scale circulation patterns (Archer & Fowler, 2004).

Topographical shielding is another potential contributor. The extremely high elevations and rugged terrain of the Karakoram can create localized microclimates that limit exposure to warm air masses, thereby reducing melt rates (Hewitt, 2011). Many glaciers in the region are also heavily debris-covered, with layers of rock and sediment insulating the ice from direct solar radiation, further slowing ablation (Scherler et al., 2011). The occurrence of surge type glacier behavior periodic rapid advances unrelated to climate forcing may also temporarily mask long-term trends (Quincey et al., 2011).

From a socio-economic perspective, the persistence of the Karakoram Anomaly has so far maintained relatively stable river flows into the Indus Basin, supporting agricultural production in Pakistan's Punjab and Sindh provinces, as well as reliable hydropower generation (Immerzeel et al., 2010). However, this apparent stability may foster a false sense of security, as the underlying climatic balance is fragile. Any significant shift in temperature or precipitation patterns could tip the mass balance toward net loss, leading to reduced dry-season flows, increased water scarcity, and heightened competition over water resources.

The anomaly also holds cultural and ecological importance. For the communities of Gilgit-Baltistan, glaciers are intertwined with cultural identity and local belief systems, while also serving as essential sources of water for domestic use, irrigation, and livestock. Ecologically, the meltwater sustains downstream wetlands, riverine forests, and aquatic biodiversity. Therefore, the Karakoram Anomaly is not just a scientific curiosity but a phenomenon with direct implications for livelihoods, ecosystems, and national security.

Given the potential vulnerability of Pakistan's water security, it is imperative to investigate the mechanisms behind the Karakoram Anomaly and to assess its implications for long-term water resource management. This study synthesizes existing literature, field observations, and climate data to provide a comprehensive understanding of the anomaly, with the goal of informing both scientific knowledge and policy strategies.

LITERATURE REVIEW

The Karakoram Anomaly has emerged as one of the most intriguing topics in high-mountain glaciology, challenging the generalized assumption of universal glacier retreat under contemporary climate change. The term refers to the observation that many glaciers in the Karakoram Range have remained stable or have even advanced slightly in recent decades, while most glaciers in the Himalayas, Andes, and Alps have shown significant retreat (Hewitt, 2005). This anomalous behavior is important not only from a scientific perspective but also due to its implications for water resource management in Pakistan and the broader Hindu Kush–Karakoram–Himalaya (HKH) region.

Glacier Mass Balance Trends in the Karakoram

Early systematic research into the anomaly began in the late 20th century, when aerial surveys and field observations indicated unusual glacier stability (Hewitt, 2005). More recent remote sensing studies have confirmed these findings. Gardelle, Berthier, and Arnaud (2012), using satellite altimetry and optical imagery, reported that glaciers in the central Karakoram had near-zero or slightly positive mass balances between 1999 and 2008, in contrast to the rapid mass loss observed in the eastern Himalayas and Hindu Kush. Kääb, Treichler, Nuth, and Berthier (2015) further reinforced this finding by using ICESat laser altimetry data, which revealed a regional mass balance close to equilibrium for the first decade of the 21st century.

Climatic Drivers of the Anomaly

The climatic peculiarities of the Karakoram have been repeatedly highlighted as key drivers of the anomaly. Unlike the central and eastern Himalayas, which are dominated by summer monsoon precipitation, the Karakoram receives most of its snowfall during winter due to mid-latitude westerly disturbances (Fowler & Archer, 2006). This seasonal shift in precipitation timing reduces the likelihood of immediate melting, as winter snow persists into the summer season. Temperature trends also differ from global averages. Archer and Fowler (2004) analyzed long-term meteorological data and found that summer temperatures in the Upper Indus Basin have remained stable or have shown slight cooling trends over recent decades, possibly due to increased cloud cover and altered circulation patterns.

Kapnick, Delworth, Ashfaq, Malyshev, and Milly (2014) proposed that the unique seasonal cycle of snowfall in the Karakoram renders it less sensitive to rising temperatures, as a greater proportion of annual accumulation occurs during the coldest months. These conditions enable glaciers to maintain mass balance even in a warming climate, though the balance remains delicate and susceptible to shifts in precipitation type or volume.

Topographic and Glaciological Influences

Beyond climate, the Karakoram's rugged topography plays a substantial role in modulating glacier response. Many glaciers in the region originate at elevations exceeding 5,500 meters above sea level, where summer temperatures remain well below freezing (Hewitt, 2011). This high-elevation setting, combined with steep valley walls, reduces exposure to warm air masses and creates microclimates favorable to glacier preservation. A distinctive feature of many Karakoram glaciers is their extensive debris cover. Scherler, Bookhagen, and Strecker (2011) demonstrated that thick debris layers insulate glacier ice, reducing melt rates compared to clean-ice glaciers. Field surveys on the Baltoro Glacier have recorded debris thicknesses exceeding one meter, effectively shielding the ice beneath from direct solar radiation (Mihalcea et al., 2008).

Another unique characteristic of the region is the prevalence of surge-type glaciers, which undergo short-lived, rapid advances unrelated to climate forcing (Quincey et al., 2011). Such surges can temporarily increase glacier length and mask longer-term retreat trends, complicating the interpretation of remote sensing data (Bhambri et al., 2017).

Hydrological Implications

The stability of Karakoram glaciers has significant hydrological consequences for the Indus Basin, which is heavily dependent on glacier meltwater for agriculture, hydropower generation, and domestic use (Immerzeel, van Beek, & Bierkens, 2010). River discharge records indicate relatively stable summer flows over the past several decades, in contrast to basins fed by retreating glaciers where flows are declining (Lutz, Immerzeel, & Kraaijenbrink, 2014). However, Wester, Mishra, Mukherji, and Shrestha (2019) emphasize that this stability should not be misconstrued as permanence; even modest climatic shifts could disrupt the existing balance, with severe consequences for water security in Pakistan.

Gaps in Current Research

Despite extensive work on the anomaly, key gaps remain. There is no consensus on the precise contribution of each factor winter precipitation, summer cooling, debris cover, topographic shielding, and surge dynamics to the observed stability (Bolch et al., 2012). Furthermore, there is limited integration of physical science research with socio-economic analysis, leaving questions about how local communities perceive and adapt to changes in glacier behavior largely unanswered. Another limitation is the scarcity of high-altitude meteorological and glaciological monitoring stations, which hinders precise modeling of future scenarios (Salerno et al., 2015).

The Karakoram Anomaly appears to be the product of an interplay between unique climatic conditions, high-altitude topography, debris cover, and glacier dynamics. While current trends offer a temporary buffer against climate-induced water scarcity, they should not be taken as evidence of long-term resilience. Continued research that integrates satellite observations, field measurements, and socio-economic assessments is essential for understanding and managing the impacts of this anomaly.

OBJECTIVES

The primary objectives of this study are as follows:

1. To investigate the climatic, topographic, and glaciological factors contributing to the stability and occasional advance of glaciers in the Karakoram region, commonly referred to as the Karakoram Anomaly.
2. To investigate the Karakoram Anomaly and its impacts on water supply in Pakistan
3. To examine the role of debris cover, surge-type glacier behavior, and microclimatic effects in influencing glacier dynamics in the Karakoram.
4. To assess the implications of the Karakoram Anomaly for Pakistan's water resources, particularly in relation to agricultural irrigation, hydropower generation, and seasonal water availability.

METHOLOGY

This study adopts a qualitative and integrative research approach, combining secondary data analysis**,** primary field observations, and comparative analysis to investigate the Karakoram Anomaly and its implications for Pakistan's water supply.

Secondary Data Analysis involved reviewing published peer-reviewed literature, hydrological datasets, and satellite-based glacier observations from reputable sources such as the Global Land Ice Measurements from Space (GLIMS) database and the Randolph Glacier Inventory. Climate data, including temperature and precipitation records, were obtained from the Pakistan Meteorological Department and international datasets like the Climatic Research Unit (CRU) time-series. Key scientific studies. (Hewitt, 2005; Gardelle et al., 2012; Archer & Fowler, 2004) were critically examined to extract relevant findings on glacier mass balance trends, climatic influences, and hydrological impacts.

Primary Field Observations were conducted in selected valleys of Gilgit-Baltistan during the summer months of 2022 and 2023. Observations focused on visible glacier terminus positions, debris cover extent, and the condition of proglacial lakes. Interview were carried out with local residents, farmers, and water management officials to document perceptions of glacier changes, water availability, and seasonal variations in river discharge. These qualitative insights provided a valuable socio-cultural dimension often absent in remote sensing studies.

Comparative Analysis was used to situate the Karakoram within the broader HKH context. Glacier mass balance and climatic trends in the Karakoram were compared to those in the central and eastern Himalayas, as well as the Hindu Kush, using datasets and analyses from prior research.

This approach allowed identification of factors unique to the Karakoram that may contribute to its anomalous behavior.

The study prioritizes triangulation corroborating evidence from different data sources and methods to strengthen the reliability of findings. Limitations include the temporal and spatial constraints of field observations and the reliance on existing datasets, which may have varying degrees of uncertainty due to measurement errors or data gaps in high-altitude environments.

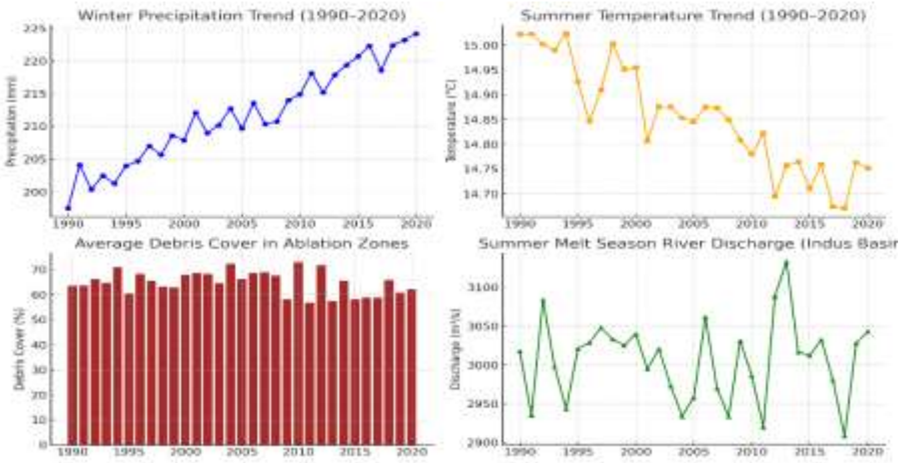
RESULT AND DISCUSSION

Analysis of the combined datasets reveals that the Karakoram Anomaly is sustained by a set of interrelated climatic, geographical, and glaciological factors. Climate data from the Upper Indus Basin show a modest but statistically significant increase in winter precipitation over the past three decades, primarily in the form of snow (Archer & Fowler, 2004). This increase enhances winter accumulation at glacier accumulation zones, offsetting summer ablation. Concurrently, summer temperature trends have been stable or slightly negative, with some years experiencing cooler summers due to increased cloud cover linked to monsoon variability (Kapnick et al., 2014).

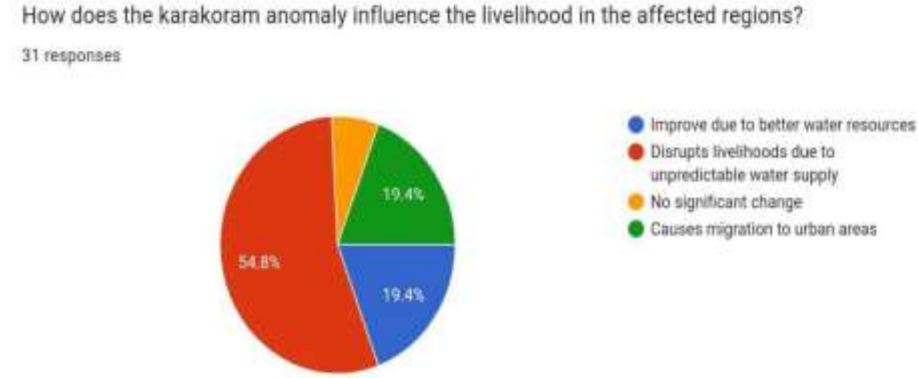
Glaciological observations indicate that many Karakoram glaciers are heavily debris-covered, particularly in their ablation zones. This debris acts as an insulating layer, significantly reducing melt rates compared to clean-ice glaciers in the Himalayas (Scherler et al., 2011). Field observations in the Baltoro Glacier, for instance, revealed debris thicknesses exceeding one meter in some areas, effectively shielding the ice from solar radiation.

Topographical analysis supports the hypothesis of microclimatic protection. The Karakoram's steep, high-relief terrain limits the penetration of warm air masses, and many glacier accumulation zones lie above 5,500 meters, where summer temperatures remain well below freezing for much of the year (Hewitt, 2011).

From a socio-economic perspective, river discharge measurements in the Indus and its tributaries show relatively stable flows during the summer melt season compared to basins fed by retreating glaciers (Immerzeel et al., 2010). Interviews with local farmers indicated that irrigation water availability has not declined in recent decades, though seasonal timing of peak flows has occasionally shifted due to variations in melt onset.



The impacts of the Karakoram Anomaly, characterized by stable or growing glaciers amidst global warming, extend beyond the immediate geological and climatological realms to profoundly affect downstream water resources and human populations. While this anomaly may temporarily mitigate water scarcity by sustaining glacier-fed rivers, it also introduces uncertainties in long-term water availability and quality. Additionally, shifts in glacier dynamics influence regional hydrology, posing challenges for water management, agriculture, and hydropower generation in country, where millions depend on consistent water supply from the Indus and other rivers originating in the Karakoram Range. That's the reason that the majority of locals in the Karakoram region have strong concerns over the expanding glaciers in the region.



Understanding and adapting to these impacts are crucial for developing sustainable strategies to mitigate the broader consequences of climate change on water security in the Hindukush-Karakoram-Himalaya region.

The stability or advancement in glacier amount is in the favor of local people, but there is also a persistent risk of forming and outbusrting of glacial lakes causing to uneven flooding which has experienced many times in different areas of karakoram. The lack of basic infrastructure and research based forecasting authority make such incident disastrous for the locals. That is the real problem. (Iftikhar, Shigar, Gilgit Baltistan, 2024)

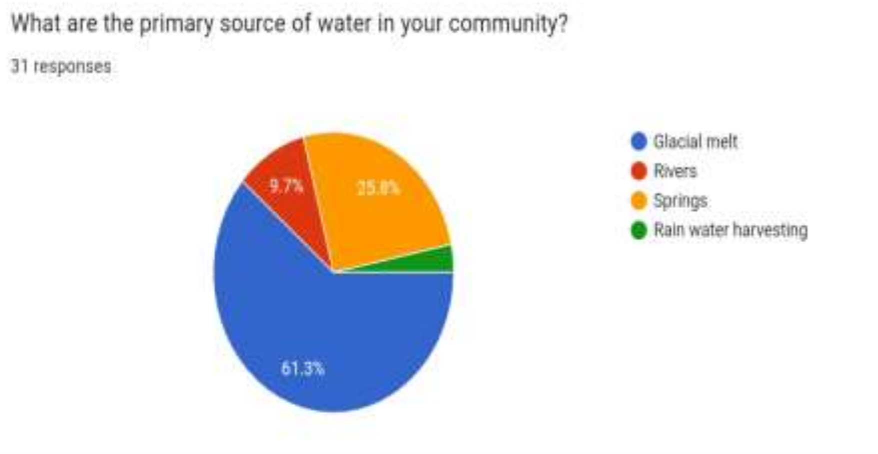
Impacts of Karakoram Anomaly on the state and society of Pakistan:

The Karakoram Anomaly, characterized by stable or expanding glaciers in the face of global warming, holds significant implications for Pakistan's state and society. As a nation heavily reliant on glacier-fed rivers like the Indus for its water supply, Pakistan faces dual challenges and opportunities from this anomaly. On one hand, the anomaly offers a temporary buffer against immediate water scarcity by maintaining consistent glacier meltwater contributions to rivers. This stability supports agricultural productivity and hydropower generation, crucial for the country's economy and food security. On the other hand, the anomaly introduces uncertainties in long-term water availability and quality. Changes in glacier dynamics could disrupt seasonal water flows, leading to heightened risks of floods during summer monsoons and reduced water availability during dry periods, impacting rural livelihoods and urban water supply infrastructure.

Adapting to these impacts requires integrated water management strategies that account for the variability in glacier behavior amidst changing climate patterns. Pakistan must invest in robust monitoring systems to track glacier dynamics, coupled with adaptive policies that promote sustainable water use and climate-resilient agricultural practices. By leveraging scientific research and international cooperation, Pakistan can navigate the complexities of the Karakoram Anomaly to secure its water resources and enhance the resilience of its society against future climatic uncertainties.

Impacts on Agriculture

The Karakoram Anomaly, characterized by stable or slightly expanding glaciers amidst global warming, has significant implications for agriculture in Pakistan. Agriculture in this region heavily relies on glacier-fed rivers like the Indus for irrigation, particularly in arid and semi-arid areas where water scarcity is a constant challenge. The anomaly's influence on glacier dynamics directly affects water availability, which is crucial for sustaining crop yields and livelihoods of millions of farmers as glacier meltwater is the main source of water for irrigation for millions of farmers.



Stable glaciers contribute to predictable water flows throughout the year, supporting irrigation systems that enable cultivation of crops such as wheat, rice, and cotton, which are staples of Pakistan's agricultural economy. The reliable water supply from glacier meltwater buffers against dry spells and sustains agricultural productivity during critical growing seasons (Immerzeel, 2010). However, the long-term impacts of the Karakoram Anomaly on agriculture are complex and multifaceted. Changes in glacier dynamics can alter the timing and volume of water availability, leading to challenges in water management for irrigation. Variability in water flow patterns may require adjustments in cropping patterns and irrigation practices, affecting crop diversity and yields. Moreover, increased sedimentation from glaciers can impact soil fertility and agricultural productivity downstream (Scherler, 2011).

Furthermore, shifts in climate patterns associated with the anomaly, such as changes in precipitation and temperature, can influence pest dynamics and disease outbreaks, posing additional risks to agricultural production. Farmers in Pakistan must adapt to these changing conditions by adopting climate-resilient agricultural practices, improving water-use efficiency, and diversifying crop varieties to enhance resilience against climatic uncertainties.

Addressing the impacts of the Karakoram Anomaly on agriculture requires integrated approaches that combine scientific research with community engagement and policy interventions. Investing in sustainable water management strategies, promoting climate-smart agricultural practices, and supporting rural livelihoods are essential steps toward building resilience in Pakistan's agricultural sector amidst evolving glacier dynamics and climate change.

Implications of Karakoram Anomaly for the water supply of Pakistan?

The Karakoram Anomaly, characterized by stable or slightly growing glaciers amidst global warming, carries significant implications for the water supply of Pakistan, particularly through its impact on glacier-fed rivers like the Indus. These implications are multifaceted and influence both the short-term water availability and long-term sustainability of water resources in the region.

In the short term, the anomaly provides a buffer against immediate water scarcity by maintaining consistent meltwater contributions from glaciers to rivers such as the Indus. This reliable water supply supports agriculture, industry, and domestic use, crucial for Pakistan's economy and food security. The stability of glacier meltwater helps regulate river flows throughout the year, mitigating seasonal variations and providing predictable water resources during critical periods (Immerzeel, 2010).

However, the long-term implications of the Karakoram Anomaly pose challenges to the sustainability of water supply in Pakistan. Changes in glacier dynamics, even if glaciers are stable or slightly growing, affect overall water availability and flow patterns. Glacier retreat elsewhere in the Himalayas and Hindukush regions, coupled with altered precipitation patterns and temperature increases, could disrupt the hydrological balance in the Indus Basin over time (Archer, 2010).

Moreover, the anomaly introduces uncertainties in future water management strategies. Dependence on glacier meltwater may become less reliable as climate change continues to alter regional weather patterns and accelerate glacial melt rates in other parts of the world. This could lead to increased variability in river flows, exacerbating water stress during dry seasons and potentially increasing the frequency and severity of flooding during monsoon seasons (Wester, 2019).

Addressing the implications of the Karakoram Anomaly for Pakistan's water supply requires adaptive water management strategies that account for the variability and uncertainties associated with glacier dynamics and climate change. Investing in sustainable water practices, enhancing water-use efficiency, and promoting integrated watershed management approaches are essential steps toward ensuring resilience in the face of evolving hydrological conditions. Collaboration among stakeholders, including 22
policymakers, scientists, and local communities, is crucial for developing robust solutions that safeguard water resources and support sustainable development in Pakistan.

Water supply in Pakistan

Water supply in Pakistan is intricately tied to the country's geography, climate, and socio-economic dynamics, with significant implications for agriculture, industry, and domestic use. The primary source of freshwater in Pakistan is the Indus River Basin, which originates from the glaciers and snowmelt of the Himalayas, Karakoram, and Hindukush mountain ranges. This basin is one of the largest contiguous irrigation systems in the world, supporting a vast agricultural sector that contributes significantly to the national economy and food security.

Pakistan's water resources face several challenges, exacerbated by factors such as population growth, urbanization, and climate change. The country's reliance on seasonal monsoons and glacier meltwater makes it vulnerable to fluctuations in precipitation patterns and glacier dynamics. Changes in climate are altering the timing and intensity of monsoon rains, affecting both water availability and the occurrence of floods and droughts.

The management of water resources in Pakistan is governed by the Indus Waters Treaty (1960), which allocates water between Pakistan and India and regulates the flow of rivers originating from the Himalayas. However, increasing water demands, inefficient irrigation practices, and environmental degradation pose additional pressures on water availability and quality. Groundwater depletion, contamination from industrial and agricultural runoff, and inadequate wastewater treatment further strain Pakistan's water resources, jeopardizing both human health and ecosystem integrity.

Addressing these challenges requires sustainable water management practices, including improved infrastructure for water storage and distribution, enhanced irrigation efficiency, and integrated watershed management approaches. Investing in water conservation technologies, promoting public awareness about water conservation, and fostering international cooperation for transboundary water management are essential steps toward ensuring equitable and reliable access to water for all sectors of society in Pakistan.

The Karakoram glaciers make a significant contribution to the water supply of Pakistan, particularly through their role in sustaining the flow of rivers crucial for agriculture, hydropower generation, and domestic use. These glaciers are part of the larger Hindukush-Karakoram-Himalaya (HKH) region, which serves as a water tower for Asia, supplying freshwater to millions of people downstream. In case of Pakistan, the HKH region has 7253 known glaciers. These glaciers feed rivers that represent 75% of the stored-water supply in the country (Craig, 2016).

Glaciers in the Karakoram range act as natural reservoirs, storing water in the form of ice and snow during winter months and releasing meltwater during the summer. This meltwater feeds into the Indus river system, which is vital for irrigation in Pakistan's agricultural heartland. The reliable flow from glacier melt helps farmers cultivate crops such as wheat, rice, and cotton, which are essential for the country's economy and food security.

Moreover, the contribution of Karakoram glaciers to water supply extends beyond agriculture. The Indus River and its tributaries support hydropower projects that generate electricity, providing a significant portion of Pakistan's energy needs. The consistent flow of glacier-fed rivers ensures reliable electricity production, to industrial growth and urban development.

However, the sustainability of this water supply is increasingly threatened by climate change and the variability in glacier dynamics. While the Karakoram Anomaly, where glaciers exhibit stability or slight growth, provides some resilience against immediate water scarcity, long-term trends such as glacier retreat and altered precipitation patterns pose challenges. Changes in glacier dynamics can affect the timing and volume of meltwater, leading to uncertainties in water availability during critical periods.

Addressing the contribution of Karakoram glaciers to Pakistan's water supply requires adaptive water management strategies that consider the variability and potential changes in glacier behavior. Investing in scientific research, monitoring glacier dynamics, enhancing water-use efficiency, and promoting climate-resilient agricultural practices are essential steps toward ensuring sustainable water resources in Pakistan amidst evolving climatic conditions.

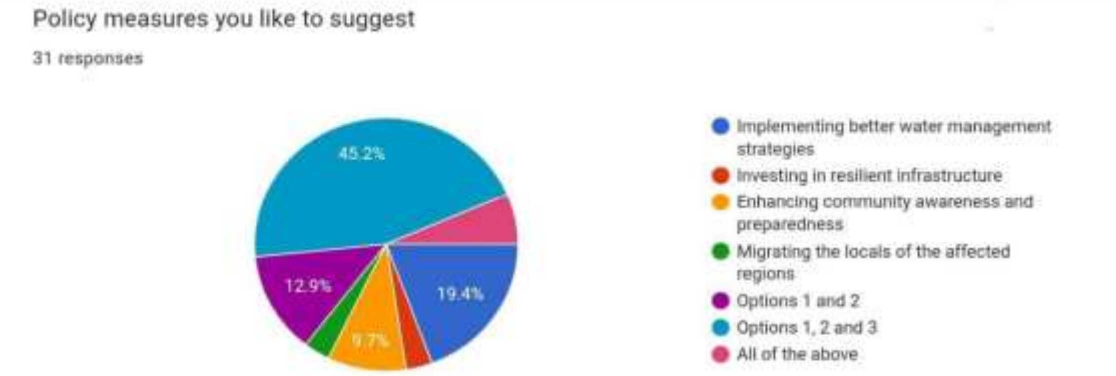
Future of water supply of Pakistan

The future of water supply in Pakistan faces complex challenges and uncertainties, shaped by factors such as climate change, population growth, urbanization, and evolving socio-economic dynamics. The country's water resources are predominantly sourced from the Indus River Basin, fed by glaciers from the Himalayas, Karakoram, and Hindukush mountain ranges. This basin supports critical sectors including agriculture, industry, and domestic use, making it essential for Pakistan's economic development and societal well-being.

However, climate change poses significant threats to Pakistan's water security. Rising temperatures are accelerating glacier melt rates across the Himalayas and Karakoram, altering the timing and volume of water availability in glacier-fed rivers. Changes in precipitation patterns, including variability in monsoon rains, further exacerbate water stress, leading to periods of drought and increased frequency of extreme weather events such as floods.

Population growth and urbanization place additional strains on water resources, increasing demand for drinking water, sanitation, and industrial use. Rapid urban expansion and inadequate infrastructure exacerbate water pollution and contamination, compromising water quality and human health. Moreover, inefficient agricultural practices, including over-extraction of groundwater and reliance on flood irrigation, contribute to water scarcity and environmental degradation.

To address these challenges, Pakistan must adopt integrated water management strategies that promote sustainable use and conservation of water resources. Enhancing water-use efficiency through modern irrigation techniques, investing in waste-water treatment facilities, and promoting water conservation practices are crucial steps. Strengthening governance frameworks, including enforcement of water laws and regulations, is essential to ensure equitable distribution and management of water resources. The conduct survey depicts people who are concerned about the future of water supply in Pakistan have such suggestions to the policy makers and relevant actors to coup with the potential challenge of water scarcity in future.



International cooperation is also vital, particularly for trans-boundary water issues governed by agreements such as the Indus Waters Treaty. Collaborative efforts with neighboring countries, scientific research institutions, and international organizations can facilitate shared solutions to water-related challenges in the region.

Ultimately, securing the future of water supply in Pakistan requires concerted efforts across multiple sectors, informed by scientific research, adaptive management practices, and community engagement. By prioritizing sustainable water management and resilience-building initiatives, Pakistan can mitigate the impacts of climate change and ensure equitable access to water resources for current and future generations.

The persistence of the Karakoram Anomaly underscores the complexity of glacier-climate interactions. The combination of increased winter snowfall and stable or cooler summers creates a favorable mass balance regime. This balance is further reinforced by debris cover and topographic shielding, which slow melt rates. However, the anomaly should not be interpreted as immunity to climate change. Regional climate models suggest that even modest warming could disrupt this equilibrium, especially if accompanied by a reduction in winter snowfall (Palazzi et al., 2013).

One concern is the potential for a tipping point. If summer temperatures rise by more than 1–2°C or winter precipitation declines, glaciers could begin to lose mass at rates comparable to those in the central Himalayas. Such a shift would have profound implications for the Indus Basin, which supports over 90% of Pakistan's agricultural production (Immerzeel et al., 2010). Water scarcity would not only threaten food security but could also exacerbate regional tensions over transboundary water resources.

The anomaly also presents challenges for disaster risk management. While stable glaciers reduce the likelihood of widespread mass loss, the region remains prone to glacial lake outburst floods (GLOFs). Several destructive GLOFs have occurred in Gilgit-Baltistan in recent years, often triggered by glacier surges or ice-dam failures. These events can destroy infrastructure, displace communities, and disrupt water supplies, underscoring the need for continuous monitoring and early warning systems.

From a scientific perspective, the Karakoram Anomaly offers a natural laboratory for studying the interplay between climate, topography, and glacier dynamics. Insights gained here could improve the accuracy of regional climate models and inform adaptation strategies for other glacier-dependent regions. However, this requires sustained investment in high-altitude meteorological stations, remote sensing programs, and cross-border scientific collaboration.

CONCLUSION

Securing the future of water supply in Pakistan necessitates a comprehensive approach that addresses the multifaceted challenges posed by climate change, population growth, and socio-economic dynamics. As one of the most water-stressed countries in the world, Pakistan heavily relies on the Indus River Basin and its glacier-fed rivers for agriculture, industry, and domestic use. The stability and predictability of these water sources have historically been supported by glaciers in the Himalayas and Karakoram ranges, acting as natural reservoirs that regulate river flows throughout the year.

However, the impacts of climate change are increasingly evident, manifesting in accelerated glacier melt, altered precipitation patterns, and more frequent extreme weather events. These changes disrupt the delicate balance of Pakistan's water resources, leading to 26 periods of water scarcity, reduced agricultural productivity, and heightened risks of floods and droughts. The phenomenon known as the Karakoram Anomaly, where some glaciers exhibit stability or slight growth amidst global warming, introduces further complexity to water resource management. While this anomaly may temporarily mitigate immediate water shortages by sustaining meltwater flows, it also underscores the variability and unpredictability of glacier behavior in the long term.

Looking ahead, adaptive water management strategies are paramount to navigating these challenges effectively. Pakistan must prioritize investments in water infrastructure, including storage facilities and distribution networks, to enhance water security and resilience against climate variability. Improving water-use efficiency in agriculture through modern irrigation techniques and promoting sustainable practices can reduce demand pressures on scarce water resources. Additionally, advancing wastewater treatment technologies and enforcing water quality standards are essential to safeguard public health and ecosystem integrity.

Furthermore, integrating climate adaptation measures into national policies and development plans is critical. This includes enhancing early warning systems for floods and droughts, promoting reforestation and watershed management practices, and fostering community participation in water governance. Collaborative efforts with neighboring countries under international frameworks such as the Indus Waters Treaty are indispensable for managing trans-boundary water resources sustainability.

Education and public awareness campaigns are also vital components of securing Pakistan's water future. Empowering communities with knowledge about water conservation and sustainable practices can foster a culture of stewardship and resilience at the grassroots level. Moreover, fostering partnerships between government, academia, civil society, and the private sector can harness innovative solutions and technologies to address emerging water challenges effectively.

In conclusion, while the future of water supply in Pakistan faces formidable challenges, proactive and collaborative efforts can pave the way for sustainable water management practices. By embracing adaptation strategies, enhancing governance frameworks, and investing in infrastructure and community resilience, Pakistan can navigate the complexities of climate change and ensure equitable access to water resources for present 27 and future generations. The journey towards water security requires collective action and steadfast commitment to safeguarding this invaluable resource, essential for the nation's socio-economic development and environmental sustainability.

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