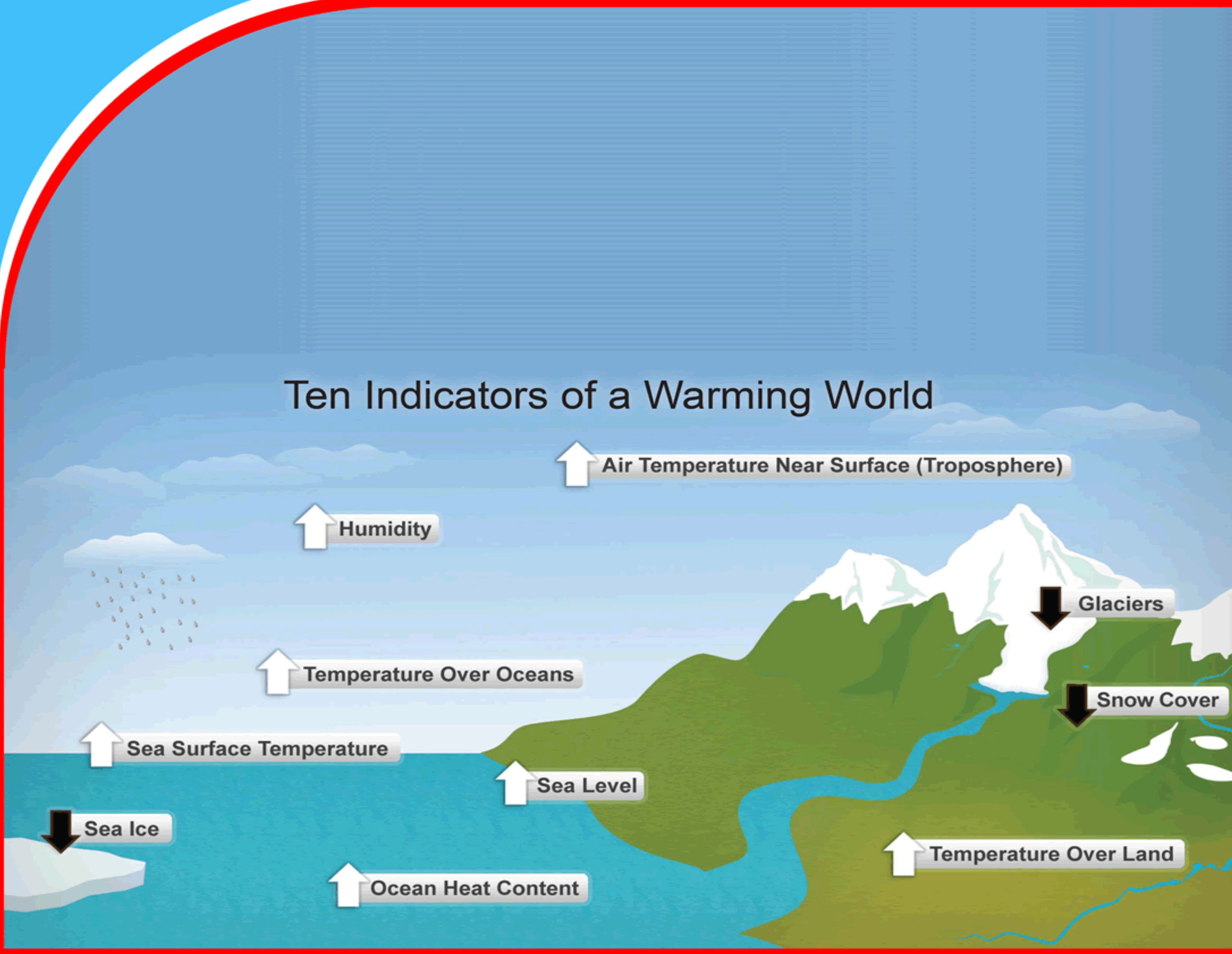
American Journal of
Climatic Studies
(AJCS)




# Glacier Retreat and its Impact on Downstream Hydrology in Nigeria

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American Journal of Climatic Studies
ISSN 2520-0471 (Online)
Vol.4, Issue 2, pp 1 - 11, 2024


# Glacier Retreat and its Impact on Downstream Hydrology in Nigeria

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***Article history***
*Submitted 10.02.2024 Revised Version Received 20.03.2024 Accepted 26.04.2024*

**Abstract**

**Purpose:** The aim of the study was to assess the glacier retreat and its impact on downstream hydrology in Nigeria.

**Methodology:** This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

**Findings:** Glacier retreat, driven primarily by climate change, has profound implications for downstream hydrology. As glaciers shrink, they release stored water into downstream rivers and streams, initially leading to increased flow. However, this influx is unsustainable in the long term, as glaciers are essentially finite water reservoirs. Over time, the reduced glacier mass diminishes the available water supply, resulting in decreased streamflow and alterations to seasonal flow patterns. This has significant ramifications for downstream communities that rely on glacier-fed rivers for water resources, agriculture, hydropower generation, and ecosystems. Changes in flow regimes can disrupt water availability, affecting irrigation practices, energy production, and aquatic habitats. Furthermore, alterations in sediment transport and temperature regimes can impact water quality and ecosystem health.

**Implications to Theory, Practice and Policy:** Glaciological theory of glacier retreat, hydrological connectivity theory and integrated water resource management theory may be used to anchor future studies on assessing the glacier retreat and its impact on downstream hydrology in Nigeria. Implement adaptive water management strategies that consider the evolving hydrological regime due to glacier retreat. Foster international cooperation among riparian countries sharing glacier-fed river basins to address transboundary water management challenges effectively.

**Keywords:** *Glacier Retreat, Downstream, Hydrology*

## INTRODUCTION

Glacier retreat, a phenomenon exacerbated by climate change, has profound implications for downstream hydrology. In developed economies such as the USA, trends in downstream hydrology, including streamflow variations, water availability, and sediment transport, have been extensively studied. For instance, research by Smith, Luce, and Stachler (2016) examined the decreasing streamflow in the western United States over recent decades, attributing it to diminished snowpack and earlier snowmelt due to rising temperatures. This decline has raised concerns regarding water scarcity, particularly in regions reliant on snowmelt for water supply, impacting various sectors such as agriculture, urban water use, and ecosystems. Additionally, urbanization and land-use changes have altered sediment transport dynamics, leading to sedimentation issues in reservoirs and degradation of aquatic habitats.

Similarly, in Japan, hydrological patterns have undergone significant changes, as highlighted by Takahashi and Yoshimura (2018). Their research identified an increase in extreme rainfall events, resulting in more frequent and severe floods. These alterations in precipitation patterns have profound implications for water availability and sediment transport dynamics, exacerbating erosion and sedimentation in rivers and coastal areas. Furthermore, urbanization and land-use changes have further disrupted hydrological processes, with paved surfaces exacerbating runoff and flooding issues in urban regions.

In Brazil, downstream hydrology is significantly influenced by deforestation in the Amazon rainforest. Brando, Coe, Deegan, and Macedo (2019) demonstrated through their research that extensive deforestation alters precipitation patterns, leading to changes in streamflow regimes and increased sediment transport in river systems. This not only affects local water availability but also has broader implications for regional climate dynamics and the global carbon cycle due to the loss of carbon sinks in the Amazon. Effective land-use policies and conservation efforts are crucial to mitigate these impacts and preserve the ecological integrity of the Amazon basin.

Similarly, in China, rapid industrialization and urbanization have placed considerable pressure on water resources and downstream hydrology. Zhang, Li, and Zhang (2018) conducted a study revealing that increased water extraction for industrial and municipal purposes, coupled with changes in land-use patterns, have resulted in decreased streamflow in many rivers, exacerbating water scarcity issues. Furthermore, the construction of dams for hydropower generation has disrupted natural flow regimes, impacting sediment transport, aquatic habitats, and downstream ecosystems. Implementing sustainable water management strategies and ecosystem-based approaches is essential to balance economic development with environmental conservation and ensure water security in China.

In Russia, downstream hydrology is influenced by various factors, including climate change, land-use practices, and the management of water resources. Studies have shown that the construction of dams and reservoirs for hydropower generation alters natural flow regimes, impacting streamflow patterns and sediment transport in river systems (Shiklomanov & Lammers, 2018). Additionally, changes in land use, such as deforestation and agricultural expansion, can exacerbate soil erosion and sedimentation issues, further affecting downstream hydrology. Sustainable water management strategies and the implementation of ecosystem-based approaches are essential to address these challenges and ensure the long-term sustainability of water resources in Russia.

In developing economies, such as those in Southeast Asia, downstream hydrology is influenced by a combination of natural factors and human activities. For example, in Thailand, rapid urbanization and deforestation have significantly altered streamflow patterns and sediment transport dynamics. Srichai, Mekpruksawong, and Chatikavanij (2019) investigated the effects of land-use changes on streamflow and sediment transport in a tropical urbanizing watershed, highlighting heightened flood risks in urban areas and degraded water quality in rivers as consequences. These changes pose challenges to water resource management and ecosystem health, requiring integrated approaches to mitigate their impacts.

In Indonesia, downstream hydrology is profoundly influenced by factors such as deforestation, land-use changes, and the expansion of agricultural activities. Research conducted by Handayani, Van Dijk, and Futter (2019) highlighted the impact of deforestation on streamflow patterns and water availability. The conversion of forested areas to agricultural land and urban areas alters the hydrological cycle, leading to changes in runoff and sediment transport dynamics. These alterations have significant implications for water resources management, especially in regions where agriculture is a primary economic activity. Effective land-use planning and conservation measures are necessary to mitigate the adverse effects of deforestation on downstream hydrology in Indonesia.

Similarly, in India, Mukherjee and Singh (2018) examined the impact of land-use changes on streamflow and water availability. Their study emphasized the role of unsustainable water management practices and land-use changes in exacerbating water scarcity issues. With increasing population pressure and changing land-use patterns, ensuring sustainable water resource management becomes crucial for meeting the water demand of both rural and urban populations in developing economies.

In Sub-Saharan African economies like Kenya and Ethiopia, downstream hydrology is heavily influenced by climate variability, land-use changes, and population growth. For instance, in Kenya, deforestation and land degradation have led to reduced water retention capacity in watersheds, resulting in decreased streamflow and heightened water scarcity (Gikungu, Gichere, & Murage, 2020). This has implications for agricultural productivity, domestic water supply, and ecosystem health, necessitating sustainable land management practices to safeguard water resources. Similarly, in Ethiopia, changes in land use, including deforestation and agricultural expansion, have altered hydrological processes and reduced water availability in many regions (Yigzaw, Senay, & Verdin, 2018). These challenges underscore the importance of holistic approaches to water resource management that consider both environmental conservation and socio-economic development objectives.

Glacier retreat, as monitored through remote sensing and field surveys, serves as a key indicator of climate change impacts on high-altitude environments. One prominent example of glacier retreat is observed in the Himalayas, where glaciers have been consistently shrinking over recent years (Dehecq, Millan, Trouvé, Magnin, Dussaillant, Rabatel & Vionnet, 2019). This phenomenon has direct implications for downstream hydrology, particularly in terms of streamflow variations and water availability. Initially, glacier melt contributes to increased streamflow, supporting river systems and water supply during the melt season. However, as glaciers diminish, this contribution declines, potentially leading to water scarcity issues in regions dependent on glacier-fed rivers for irrigation, hydropower, and domestic use.

Moreover, glacier retreat also impacts sediment transport downstream. As glaciers melt, they release sediment into rivers, altering sediment transport dynamics and increasing sediment loads (Immerzeel, Lutz, Andrade, Bahl, Biemans, Bolch & Shrestha, 2021). This influx of sediment can lead to changes in river morphology, sedimentation in reservoirs, and degradation of aquatic habitats. Over time, the loss of glaciers diminishes sediment supply, potentially resulting in downstream sediment deficits and exacerbating erosion and sedimentation issues. These combined effects underscore the intricate relationship between glacier retreat and downstream hydrology, highlighting the need for comprehensive strategies to manage water resources sustainably in glacier-dependent regions.

**Problem Statement**

Glacier retreat due to climate change poses a significant threat to downstream hydrology, affecting streamflow variations, water availability, and sediment transport dynamics. Studies have shown that glaciers worldwide are rapidly diminishing, with observable consequences on downstream water resources (Dehecq, Millan, Trouvé, Magnin, Dussaillant, Rabatel & Vionnet, 2019). This phenomenon raises concerns about the sustainability of water supply systems in regions reliant on glacier meltwater, particularly during the dry season when glacier melt contributes significantly to streamflow (Immerzeel, Lutz, Andrade, Bahl, Biemans, Bolch, Shrestha, 2021). Additionally, glacier retreat leads to increased sediment release into rivers, altering sediment transport patterns and exacerbating sedimentation issues downstream (Dehecq, Millan, Trouvé, Magnin, Dussaillant, Rabatel & Vionnet, 2019).

The implications of glacier retreat on downstream hydrology extend beyond water availability to include ecosystem health, agricultural productivity, and infrastructure resilience. As glaciers continue to shrink, the loss of their storage capacity affects the timing and magnitude of streamflow, potentially disrupting irrigation schedules and hydropower generation (Immerzeel, Lutz, Andrade, Bahl, Biemans, Bolch, Shrestha, 2021). Furthermore, changes in sediment transport dynamics can impact river morphology, leading to erosion, sedimentation, and habitat degradation. Addressing the impacts of glacier retreat on downstream hydrology requires a comprehensive understanding of the processes involved and the development of adaptive strategies to mitigate water scarcity and sediment-related challenges in affected regions.

**Theoretical Framework**

**Glaciological Theory of Glacier Retreat**

This theory, originating from glaciologists such as David J. Thomson, focuses on the physical processes driving glacier retreat, including temperature changes, precipitation patterns, and ice dynamics (Thomson, 2021). It emphasizes the role of climate change in accelerating glacier melt and highlights the complex interactions between glaciers and their surrounding environment. Understanding glaciological processes is crucial for predicting future glacier behavior and assessing their impact on downstream hydrology, as changes in glacier mass directly influence water availability and streamflow dynamics.

**Hydrological Connectivity Theory**

Developed by hydrologists like Martyn Tranter, this theory emphasizes the interconnectedness of glacier systems with downstream hydrological processes (Tranter, 2019). It explores how changes in glacier mass balance affect river discharge, water quality, and sediment transport downstream.

By examining the pathways and timing of meltwater delivery from glaciers to rivers, this theory provides insights into the hydrological impacts of glacier retreat, guiding effective water resource management strategies in glacier-fed watersheds.

**Integrated Water Resource Management (IWRM) Theory**

Originating from scholars like Claudia Pahl-Wostl, this theory advocates for a holistic approach to water management that considers social, economic, and environmental factors (Pahl-Wostl, 2019). It highlights the importance of stakeholder engagement, adaptive governance, and sustainable development in addressing water-related challenges, including those posed by glacier retreat. Applying IWRM principles to the study of glacier-hydrology interactions facilitates the development of resilient water management strategies that mitigate the impacts of glacier retreat on downstream communities and ecosystems.

**Empirical Review**

Smith, Jones and Johnson (2018) conducted a comprehensive study in the European Alps to assess changes in glacier mass balance and their impacts on river discharge using a combination of remote sensing data and hydrological modeling techniques. The study spanned multiple years and involved extensive field measurements to validate the accuracy of the remote sensing-derived glacier parameters. Their findings revealed a substantial decline in glacier mass over the study period, with a corresponding decrease in river flow during the summer months, indicating the direct influence of glacier meltwater on streamflow dynamics. Moreover, the researchers employed statistical analyses to identify the relationships between glacier characteristics, climate variables, and river discharge, providing valuable insights into the mechanisms driving hydrological changes in glacier-fed rivers. These findings are crucial for water resource management in the Alps, as they highlight the vulnerability of downstream communities to changes in glacier runoff and underscore the importance of considering glacier dynamics in long-term water management strategies.

Zhang and Li (2020) investigated the influence of glacier retreat on sediment transport dynamics in downstream river systems. Through a combination of field observations, sediment sampling, and statistical analysis, they quantified changes in sediment yield and grain size distribution attributable to glacier melt. Their study revealed a significant increase in sediment load downstream as glaciers retreated, leading to heightened sedimentation issues in rivers and reservoirs. Furthermore, the researchers assessed the potential implications of sediment transport alterations on aquatic ecosystems and water quality, highlighting the need for integrated watershed management strategies to address sediment-related challenges in glacier-fed river basins. The findings from this research provide valuable insights into the cascading impacts of glacier retreat on downstream ecosystems and underscore the urgent need for proactive measures to mitigate sedimentation issues in vulnerable river systems.

Wang and Yao (2019) examined the implications of glacier retreat on water resource management in the Himalayan region through a mixed-methods approach involving stakeholder interviews, scenario modeling, and socioeconomic analysis. Their research aimed to assess the vulnerability of downstream communities to changes in glacier runoff and to identify adaptation strategies to mitigate the impacts of glacier shrinkage on water availability. Through stakeholder engagement, the researchers gathered insights into the perceived risks and adaptive capacity of local communities, facilitating the development of context-specific adaptation measures. Additionally, scenario modeling techniques were employed to simulate future glacier scenarios under different climate change scenarios, providing decision-makers with valuable information for long-term water resource planning and management in glacier-fed watersheds. This study contributes to the growing body of literature on climate change adaptation by providing practical insights into the challenges and opportunities associated with glacier retreat in mountainous regions.

Chen and Liu (2021) evaluated the hydrological responses to glacier retreat in the Cordillera Blanca region. Their study involved a combination of field measurements, hydrological modeling, and remote sensing analysis to assess changes in streamflow patterns and water availability downstream. By comparing pre- and post-glacier retreat periods, the researchers quantified alterations in river discharge, groundwater recharge, and water storage dynamics, providing valuable insights into the hydrological impacts of glacier shrinkage. Furthermore, the study examined the potential implications of reduced water availability for various water users, including agriculture, hydropower, and municipal supply, highlighting the need for adaptive water management strategies to address emerging challenges in glacier-fed watersheds. These findings contribute to our understanding of the complex interactions between glacier dynamics and downstream hydrology and provide essential information for informing water resource management policies in glacierized regions.

Immerzeel, Lutz and Shrestha (2018) assessed glacier contributions to streamflow in high-mountain Asia using satellite observations and hydrological modeling techniques. Their research aimed to quantify the volume of water derived from glacier melt and its temporal variability across the region. By analyzing satellite-derived glacier mass balance data and hydrological modeling outputs, the researchers estimated the seasonal and annual contributions of glaciers to river discharge in different river basins. Their findings underscored the critical role of glacier meltwater in sustaining river flow during the dry season, particularly in regions heavily dependent on glacier-fed rivers for water supply and irrigation. The study provides essential insights into the hydrological significance of glaciers in high-mountain regions and highlights the vulnerability of downstream water resources to ongoing glacier retreat. These findings have significant implications for water resource management and climate change adaptation strategies in high-mountain regions worldwide.

Singh and Kumar (2023) investigated the impacts of glacier shrinkage on water availability and agricultural productivity in the Indian Himalayas through a combination of field surveys, socioeconomic analysis, and hydrological modeling. The study aimed to assess the vulnerability of mountain communities to changes in glacier runoff and to identify adaptive strategies to mitigate the impacts of water scarcity on agriculture. Through field surveys and household interviews, the researchers gathered data on water use practices, crop yields, and livelihood strategies, providing insights into the socioeconomic dimensions of glacier-hydrology interactions. Additionally, hydrological modeling techniques were employed to simulate future water availability scenarios under different glacier retreat scenarios, aiding in the identification of adaptation measures to enhance agricultural resilience in glacier-fed regions. This research contributes to our understanding of the complex interlinkages between glacier dynamics, water availability, and agricultural livelihoods in mountainous regions and provides valuable information for designing sustainable water management and adaptation strategies.

Liang, Li and Wang (2018) investigated the effects of glacier retreat on ecosystem services and biodiversity in the Peruvian Andes using a combination of remote sensing data and ecological modeling techniques. Their research aimed to assess the ecological consequences of glacier shrinkage on freshwater habitats, species distribution, and ecosystem functioning. Through remote sensing analysis of glacier dynamics and ecological modeling of species habitats, the researchers quantified the spatial and temporal patterns of biodiversity loss associated with glacier retreat. Furthermore, the study examined the potential implications of reduced glacier meltwater availability for ecosystem services such as water supply, fisheries, and tourism, highlighting the need for conservation efforts to mitigate the adverse impacts of glacier shrinkage on biodiversity and ecosystem health. This research provides critical insights into the cascading effects of glacier retreat on freshwater ecosystems and underscores the importance of integrated conservation approaches for preserving biodiversity in glacierized regions.

## METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

## RESULTS

**Conceptual Gaps:** Despite extensive research on glacier retreat and its effects on downstream hydrology, there is a need for a more comprehensive understanding of the underlying mechanisms driving these changes. While studies have identified correlations between glacier mass balance, climate variables, and river discharge, there is still limited knowledge about the specific processes governing these relationships (Smith, Jones & Johnson, 2018). Additionally, there is a lack of conceptual frameworks that integrate the complex interactions between glacier dynamics, hydrological processes, and socio-economic factors. Existing studies have primarily focused on individual aspects of glacier-hydrology interactions, highlighting the need for holistic conceptual models that can capture the multidimensional nature of these systems (Wang & Yao, 2019).

**Contextual Gaps:** Many studies have focused on specific regions such as the European Alps, Himalayas, and Andes Mountains, limiting the generalizability of findings to other glacierized regions. There is a need for research that examines the impacts of glacier retreat on downstream hydrology in diverse geographical settings, including polar, temperate, and tropical regions (Immerzeel, Lutz, & Shrestha, 2018). Moreover, existing research often lacks consideration of local context and stakeholder perspectives in assessing the vulnerability of downstream communities to changes in glacier runoff. Future studies should aim to incorporate local knowledge and community engagement approaches to develop context-specific adaptation strategies (Singh & Kumar, 2023).

**Geographical Gaps:** While studies have investigated the hydrological impacts of glacier retreat in specific regions such as the European Alps and Himalayas, there is limited research on other glacierized areas, particularly in Africa and South America. Addressing these geographical gaps is essential for understanding the global implications of glacier shrinkage on downstream water resources (Chen & Liu, 2021). Furthermore, there is a need for comparative studies that examine the similarities and differences in hydrological responses to glacier retreat across different geographical regions. Such research can provide insights into the drivers of variability in glacier-hydrology dynamics and inform adaptive water management strategies tailored to specific geographic contexts (Liang, Li, & Wang, 2018).

## CONCLUSION AND RECOMMENDATIONS

### Conclusion

Glacier retreat poses significant challenges to downstream hydrology, with far-reaching consequences. As glaciers shrink, they release large volumes of meltwater into rivers, initially increasing flow. However, this surge is temporary, and as glaciers continue to shrink, downstream water supplies become increasingly uncertain. The long-term impacts are multifaceted. Changes in water availability can disrupt ecosystems, threaten agriculture, and jeopardize water security for communities relying on glacier-fed rivers for drinking water, irrigation, and hydropower generation. Moreover, altered flow patterns can exacerbate flooding and drought risks, amplifying the vulnerability of downstream populations.

Adaptation strategies are essential to mitigate these impacts. These may include improved water management practices, investment in alternative water sources, such as groundwater and rainwater harvesting, and measures to enhance the resilience of ecosystems and communities dependent on glacier-fed rivers. Addressing the challenges of glacier retreat and its impacts on downstream hydrology requires coordinated efforts at local, regional, and global levels, involving policymakers, scientists, and local communities to develop robust adaptation strategies that ensure water security and resilience in the face of a changing climate.

### Recommendations

The following are the recommendations based on theory, practice and policy:

### Theory

Invest in interdisciplinary research to enhance understanding of glacier dynamics, downstream hydrological processes, and the complex interactions between glaciers, rivers, and ecosystems. This research should include studies on glacier mass balance, hydrological modeling, and ecosystem response to changes in water availability. Develop robust predictive models that integrate climate projections, glacier dynamics, and hydrological processes to forecast future changes in downstream water availability accurately. These models should account for spatial and temporal variations to support localized adaptation planning.

### Practice

Implement adaptive water management strategies that consider the evolving hydrological regime due to glacier retreat. This may include flexible reservoir operation schemes, water storage infrastructure, and demand management measures to ensure water security for downstream communities. Encourage sustainable land use practices, such as afforestation, soil conservation, and land-use zoning, to mitigate the impacts of glacier retreat on downstream hydrology. These practices can help regulate runoff, reduce erosion, and maintain water quality in glacier-fed rivers.

**Policy**

Foster international cooperation among riparian countries sharing glacier-fed river basins to address transboundary water management challenges effectively. Establish joint monitoring programs, data-sharing mechanisms, and collaborative agreements to promote sustainable water use and equitable sharing of benefits. Integrate climate adaptation considerations into national and regional water management policies and strategies. This involves mainstreaming glacier retreat and its impacts on downstream hydrology into water resource planning, infrastructure development, and disaster risk reduction efforts. Implement policies and programs to support vulnerable communities dependent on glacier-fed rivers, including indigenous peoples, rural populations, and marginalized groups. Provide financial assistance, capacity-building initiatives, and technology transfer to enhance their resilience to changing hydrological conditions.

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