Integrated Hydrological Modeling in Glaciated Mountain Basins: A Case Study in the Tien-Shan Mountains of Kyrgyzstan

(氷河山地流域における統合水文モデリング：キルギスの天山山脈における事例研究)

Doctoral Thesis

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Abstract

This study focuses on integrated hydrological modeling in glaciated mountain basins, using the Tien-Shan Mountains of Kyrgyzstan as a case study. The research aims to understand the impacts of climate change on water resources in mountainous regions and develop effective framework to assess runoff sources in highly glaciated areas for water resource management and climate change risk assessment. The study begins by highlighting the vulnerability of mountainous areas to climate change, including rising temperatures, shrinking glaciers, altered precipitation patterns, and increased risks of natural hazards. These changes have profound implications for water resources, economic development, and social stability.

Mountainous regions, characterized by high elevations, steep slopes, and fragile ecosystems, are highly sensitive to environmental changes. The cascading effects of climate change in these regions disrupt the delicate balance of ecosystems and have far-reaching consequences for both human and natural systems.

One of the most significant impacts of climate change in mountainous regions is the melting of glaciers and permafrost, leading to reduced water availability during critical periods. This poses challenges for communities relying on glacial runoff for water supply and agricultural activities.

Central Asia, with its arid climate, is particularly susceptible to the effects of climate change on water resources. Glaciers and snowmelt play a vital role in the overall water balance of the region. Changes in seasonality of flow and peak water availability can have profound socio-economic implications, potentially exacerbating domestic tensions. The water resources system in Central Asia faces multiple challenges driven by climate change and other interconnected factors. Rising temperatures have resulted in earlier snowmelt, leading to peak river flows in spring and reduced discharge during the irrigation season. This, combined with the near-complete depletion of the Aral Sea, exacerbates water scarcity in the region. Maintaining the current water policy in Central Asia could impede economic growth due to water scarcity. Improving water use efficiency in the economy can contribute to expanding agricultural production, developing "green" energy, and preserving environmental assets. Changes in water use patterns will have a significant impact on economic growth, highlighting the importance of sound water resource management.

Glaciers in Central Asia have decreased by approximately one-third over the past century, with Tajikistan and Kyrgyzstan having the largest glacier-covered areas. The shrinking glaciers in the region have significant implications for water availability and stability.

This study employs integrated hydrological modeling to assess the impacts of climate change on water resources in the Tien-Shan Mountains. It utilizes models such as SiBUC, GLIMB, RRI, and temperature-index models to simulate the hydrological processes in the study area. The research involves data collection and preprocessing, including precipitation data, to feed into the models. The study area encompasses areas of the Issyk-Kul Lake Basin, Chon-Kyzyl-Suu River Basin, and Naryn River Basin. The study evaluates meteorological forcing and model simulations to assess their accuracy in representing the hydrological processes in the Tien-Shan Mountains. It also examines the impact of topographic downscaling on ice and snow melt processes and compares model results with measurements on Bordu Glacier. The research provides insights into the hydrological dynamics and factors influencing runoff in glaciated basins. By understanding these processes, effective strategies for water resource management and climate change risk assessment can be developed.

The findings of this study contribute to the understanding of integrated hydrological modeling in glaciated mountain basins. They have implications for water resource management, climate change risk assessment, and sustainable development in Central Asia. Addressing the challenges posed by climate change and developing effective adaptation strategies are crucial for ensuring the resilience of ecosystems, economies, and societies in mountainous regions. The study acknowledges the limitations and constraints of the research, providing recommendations for future research in the field of integrated hydrological modeling and climate change impacts on water resources in mountainous regions.

In conclusion, this study provides valuable insights into the impacts of climate change on water resources in glaciated mountain basins, by analyzing impact on each runoff source. It emphasizes the importance of integrated hydrological modeling in understanding and managing these impacts. The findings contribute to the knowledge base of water resource management and climate change adaptation strategies in Central Asia and beyond.

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Chapter 1: Introduction

1.1 Background

Climate change is a global phenomenon that poses significant challenges to various ecosystems and regions across the world. One such region that is particularly vulnerable to the impacts of climate change is mountainous areas.

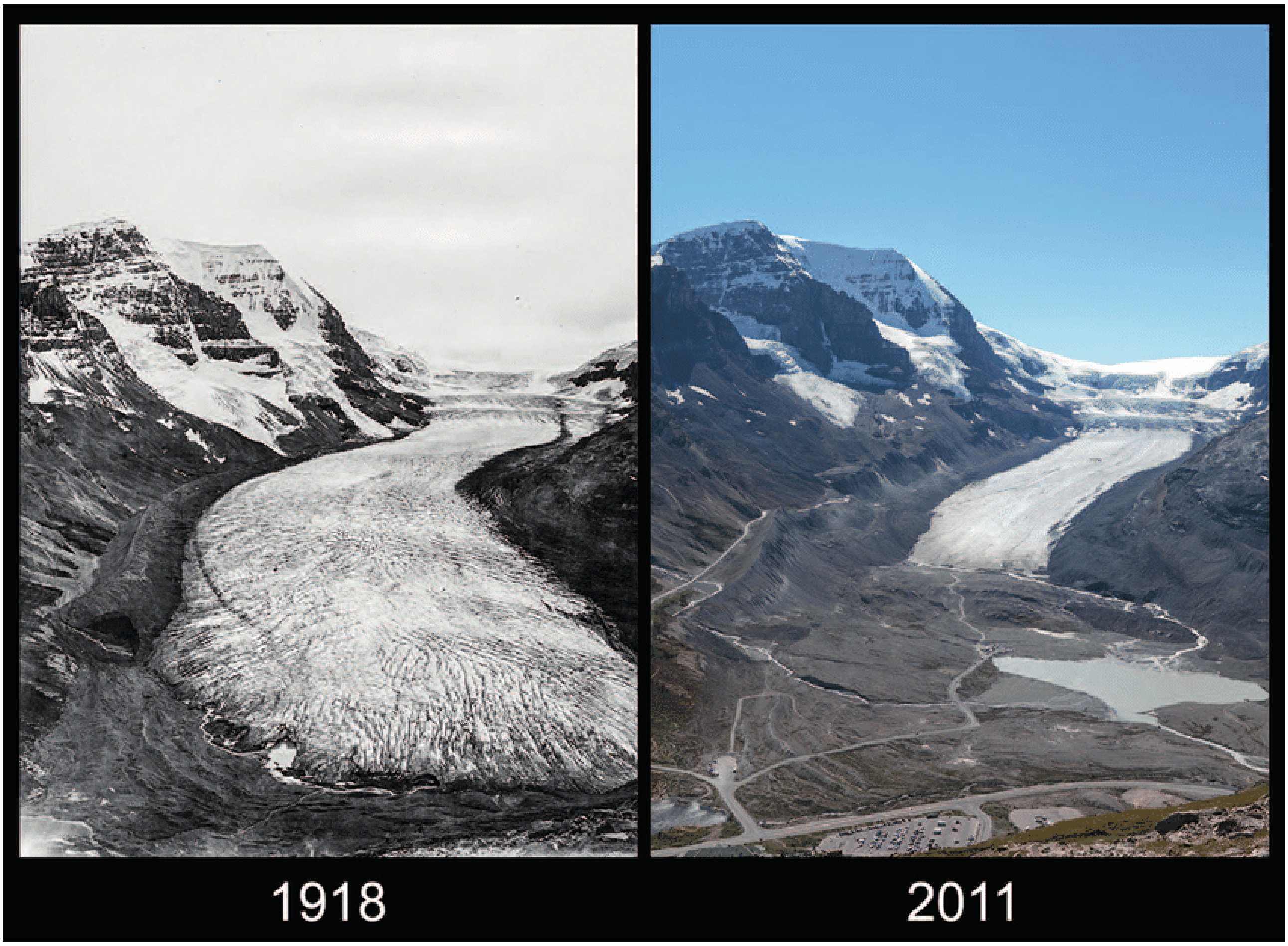

Figure 1.1: The Athabasca Glacier (52812 0 N, 117815 0 W) in Jasper National Park, Alberta, Canada (Sanseverino et al., 2016).

These regions are experiencing rising temperatures, shrinking glaciers, altered precipitation patterns, and increased risks of natural hazards (Hock and Huss, 2021; Pepin et al., 2015). The consequences of these changes extend beyond environmental concerns and have profound implications for water resources, economic development, and social stability.

The effects of climate change on mountainous regions have garnered increasing attention due to their unique geographical features and ecological importance. Mountainous areas are characterized by high elevations, steep slopes, and often fragile ecosystems, making them highly sensitive to environmental changes. The cascading effects of climate change in these regions can disrupt the delicate balance of ecosystems and have far-reaching consequences for both human and natural systems.

One of the most significant impacts of climate change in mountainous regions is the melting of glaciers and permafrost (Figure 1.1). Glaciers act as natural reservoirs, storing water in the form of ice and releasing it gradually during the warmer months. However, with rising temperatures, glaciers are rapidly retreating, leading to reduced water availability during critical periods (Rasul and Molden, 2019). This poses severe challenges for communities that rely on glacial runoff for their water supply and agricultural activities.

Central Asia, with its arid climate, is particularly susceptible to the effects of climate change on water resources (Figure 1.2). Glaciers and snowmelt contribute significantly to the overall water balance in this region (Immerzeel et al., 2010; Chen et al., 2016). The changing seasonality of flow and peak water availability can have profound socio-economic implications, potentially exacerbating domestic tensions (Bernauer and Siegfried, 2012). The reliance on glacial runoff and the potential reduction in its availability by the end of the century raise concerns about water security and stability in Central Asia (Sorg et al., 2012; Huss and Hock, 2018; Van Tricht and Huybrechts, 2023).

The water resources system in Central Asia is facing multiple challenges, primarily driven by climate change and other interconnected factors. The region is already experiencing the impacts of climate change, with average temperatures having risen by 0.5°C and projected increases of 1.6-2.6°C by 2030-2050 (IPCC AR5, 2014). These changes, combined with the near-complete depletion of the Aral Sea, exacerbate water scarcity in the region (World Bank, 2009).

One of the key effects of rising temperatures is the earlier snowmelt, leading to peak river flows in the spring and reduced discharge during the irrigation season. It is estimated that irrigation water availability could decrease by almost 25% (Huss et al., 2018). Although there is currently an increase in runoff volumes due to rapid glacier melting, future projections suggest a sharp decrease in runoff by around 2050 (Farinotti, 2015).

The consequences of climate change extend to various sectors of the economy crucial for the growth and development of the region, including energy, agriculture, and disaster risk management systems. Natural disasters caused by meteorological events already cost approximately 1% of GDP per year in a transboundary context (Third National Communication of the Kyrgyz Republic, 2016). Developing an adaptation plan to address these consequences is vital for sustainable development.

Figure 1.2: Water Management of Central Asia (Adapted from Wikipedia and CA Water Info, 2017)

Maintaining the current water policy in Central Asia could significantly impede economic growth due to water scarcity. However, improving water use efficiency in the economy can contribute to expanding agricultural production, developing "green" energy, and preserving the region's environmental assets. Changes in water use patterns will have the most significant impact on economic growth in Central Asia, emphasizing the importance of sound water resource management in mitigating the consequences of climate change.

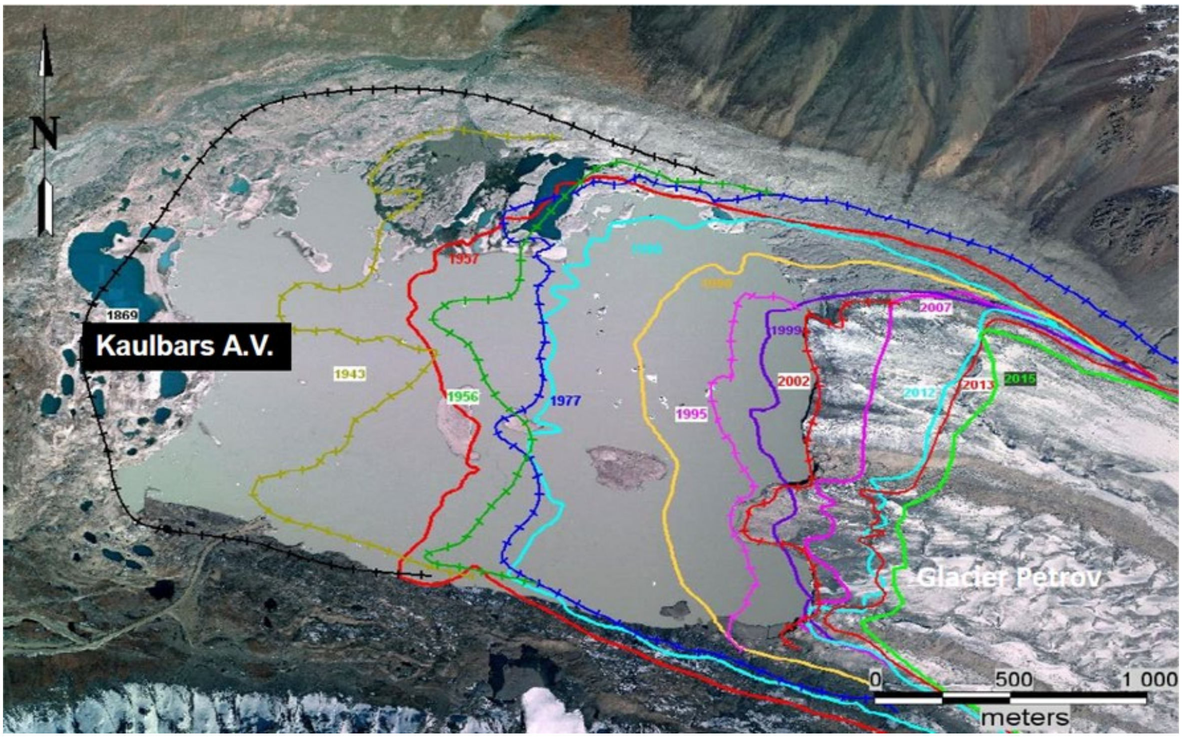

Figure 1.3: Change of Petrov glacier tongue boundaries between 1869 to 2015, according to A.V Kaulbars 1869, Kuzmichenok and Mandychev.

The impact of climate change is particularly evident in the mountainous regions of Central Asia, where glaciers have decreased by approximately one-third over the past century (Figure 1.3). Tajikistan and Kyrgyzstan have the largest glacier-covered areas, with glaciers in Kazakhstan and Uzbekistan also experiencing retreat. The total area covered by glaciers in the region is 27,677 km2, with an annual melting rate of 0.6-0.8% (Orlovskiy, 2019).

The melting of glaciers, disappearance of permafrost zones, and shrinking snow cover will further reduce the water resources in Central Asia. Additionally, high temperatures and intensive precipitation will increase the frequency of natural disasters such as droughts, heatwaves, floods, landslides, mudslides, and avalanches. Floods, in particular, are common throughout the region, accounting for 48% of recorded natural disasters between 1990 and 2011. These floods are caused by heavy rains, melting snow, and glacial mass in mountain areas, as well as the breach of glacial lakes. Over the past decade, more than 2,500 people have lost their lives due to natural disasters, with approximately 5.5 million people, or 10% of the population of Central Asia, affected by their adverse impacts (Ministry of Emergency Situations of Kyrgyzstan, 2014).

Understanding and addressing these challenges are crucial for the sustainable management of water resources and the overall development of Central Asia. By conducting comprehensive research and implementing effective adaptation strategies, the region can mitigate the impacts of climate change and ensure the resilience of its ecosystems, economies, and societies.

1.2 Research Gap

Accurately predicting the amount of meltwater generated from snowpacks is crucial for various applications, such as water resource management and climate change risk assessment (Leavesley, 1994). Hydrological models have emerged as popular methods for determining the sources of runoff in glacial basins, particularly in mountainous regions (Farinotti et al., 2012; Immerzeel et al., 2013; Luo et al., 2018; Ragettli et al., 2015). Physically based hydrological models are known for their ability to accurately describe natural processes, but they require extensive data sets to produce reliable results (Finger et al., 2011). Incorporating radiation data into these models is essential for improving their performance, especially in estimating glacier melt (Pellicciotti et al., 2011).

However, the influence of glacier dynamics on streamflow response in river basins has been identified as a complex issue due to the limitations of existing physically based distributed hydrological models in representing glacier dynamics (Naz et al., 2014). This limitation hinders the accurate estimation of glacier melt and its contribution to overall runoff. Additionally, when considering the integration of radiation data and glaciological models, the issue of downscaling the radiation data becomes relevant (Eidhammer et al., 2021). Downscaling radiation data is particularly significant in the context of glacier melt estimation and its subsequent impact on overall runoff.

The integration of radiation data and glaciological models in physically based hydrological modeling presents several challenges. First, downscaled radiation data is necessary to improve the accuracy of glacier melt estimation, as the spatial and temporal resolution of available radiation data may not align with the requirements of the models. The downscaling process involves translating coarse-scale radiation data to finer scales that are more representative of the local conditions. This downscaling process must be carefully performed to ensure the accuracy and reliability of the results.

Second, the incorporation of downscaled radiation data into glaciological models introduces another layer of complexity. The interaction between radiation and glacier dynamics is intricate, and accurately representing this relationship is essential for capturing the true melt processes. The downscaled radiation data must be integrated into the glaciological models in a manner that accurately reflects the local conditions and accounts for the complex feedback mechanisms between radiation, glacier melt, and runoff.

Addressing these challenges is vital for enhancing the accuracy and reliability of hydrological models in glacier-dominated watersheds. By improving the integration of downscaled radiation data and glaciological models, researchers can gain a better understanding of the dynamics of glacier melt and its contribution to overall runoff. This knowledge is crucial for effective water resource management and climate change risk assessment in mountainous regions, where the impacts of climate change are particularly pronounced. Further research in this area is needed to develop innovative approaches and methodologies that can overcome these challenges and improve the predictive capabilities of hydrological models in glacier-dominated watersheds.

1.3 Research Objectives

In this study, our primary objective is to utilize a cutting-edge land surface model with an integrated glaciological model to determine the runoff components of glaciated basins in the inner Tien-Shan. By incorporating the glaciological model into the land surface model, we can accurately represent the complex processes of ice and snow melt in high mountain conditions. This integrated approach allows us to assess the contribution of glacier melt to overall runoff and understand the hydrological dynamics in these glaciated basins.

To ensure the accuracy of our modeling framework, we will employ gridded reanalysis meteorological forcing data. These data will be carefully validated using observational data to ensure their reliability in representing the meteorological conditions in the study area. The preprocessing stage of the data will focus on performing topographic downscaling of incoming solar radiation. This downscaling process will account for factors such as slope, aspect, shading by surrounding topography, and cloudiness at a specific time. By considering these factors, we can accurately represent the spatial and temporal distribution of radiation, which plays a crucial role in ice and snow melt processes.

Another important objective of our study is to compare the results of discharge, the mass balance of reference glaciers, and Snow Water Equivalent (SWE) with observed data. This comparative analysis will allow us to assess the performance of the integrated model in simulating the hydrological processes in glaciated basins. By comparing the model results with observed data, we can evaluate the accuracy and reliability of our modeling framework and identify any potential areas for improvement.

Through this research, we aim to gain a better understanding of the hydrological dynamics in glaciated basins and the role of various factors, such as radiation, in influencing runoff. The comprehensive analysis of the model results and their comparison with observed data will provide crucial insights into the accuracy and reliability of the modeling framework.

Additionally, this research will contribute to validating the performance of the integrated model in simulating the hydrological processes at each stage in the study area.

Overall, the objectives of this study are to accurately represent the hydrological processes in glaciated basins, assess the contribution of glacier melt to overall runoff, and validate the performance of the integrated model using observed data. By achieving these objectives, we can enhance our understanding of the complex dynamics of water resources in high mountain regions and contribute to improved water resource management and climate change risk assessment in the inner Tien-Shan.

1.4 Significance of the Study

The significance of this study lies in its contribution to the understanding and management of water resources in arid mountainous basins, both locally and globally. Arid mountainous basins are particularly vulnerable to the impacts of climate change, as they are characterized by limited water availability and are highly dependent on glacial meltwater. Therefore, accurately predicting and assessing the runoff components in these basins is essential for sustainable water resource management and climate change adaptation strategies. By utilizing a land surface model with an integrated glaciological model, this study provides a comprehensive and advanced approach to understanding the hydrological dynamics in glaciated basins. The integration of these models allows for a more accurate representation of the complex processes of ice and snow melt, which is crucial for estimating the contribution of glacier melt to overall runoff.

Furthermore, the insights gained from this study can be applied to other arid mountainous basins worldwide. Many regions, such as the Andes, the Himalayas, and the Rocky Mountains, face similar challenges in terms of water scarcity and the reliance on glacial meltwater. The integrated modeling approach and the methodologies employed in this study can serve as a valuable reference for researchers and practitioners working in these regions.

Additionally, this study contributes to the broader field of hydrological modeling and research. The integration of glaciological models into land surface models represents an advancement in our understanding of the complex interactions between glaciers, climate, and hydrology. The insights gained from this study can contribute to the refinement and improvement of hydrological models in general, enhancing their ability to accurately simulate water resource dynamics in various settings.

1.5 Research Questions

Considering the significance of this study in understanding and managing water resources in arid mountainous basins, several research questions can be formulated. These questions aim to address the key aspects of the hydrological dynamics in glaciated basins and the role of various factors in influencing runoff. Here are some potential research questions:

1) How accurately can the integrated land surface model with the glaciological model represent the hydrological processes in glaciated basins in arid mountainous regions?
2) What is the contribution of glacier melt to overall runoff in these basins, and how does it vary spatially and temporally?
3) How do different factors, such as radiation, topography, and meteorological conditions, influence the ice and snow melt processes in these basins?
4) What is the accuracy and reliability of downscaled radiation data in estimating glacier melt and its impact on runoff?
5) How well do the model results of discharge, mass balance of reference glaciers, and Snow Water Equivalent (SWE) compare with observed data, and what insights can be gained from this comparison?
6) What are the implications of the findings for water resource management and climate change adaptation strategies in these arid mountainous basins?
7) What are the limitations and uncertainties associated with the integrated model and the methodologies used, and how can they be addressed or minimized?
8) What are the potential future scenarios for water resources in these basins under climate change, and how can this information be used for sustainable water management planning?

These research questions will guide the study in investigating the complexities of hydrological processes in glaciated basins in arid mountainous regions and contribute to the advancement of knowledge in this field. By addressing these questions, the study aims to provide valuable insights into water resource management, climate change adaptation, and the improvement of hydrological modeling approaches in arid mountainous basins worldwide.

1.6 Research Methodology

In this research, we aim to accurately quantify the sources of runoff and understand the hydrological processes in glaciated mountain basins within the inner Tien-Shan mountains of Kyrgyzstan. To achieve this, we have employed an integrated modeling approach, combining land surface, glacier energy-mass balance, and river routing models (Figure 1.4).

The first step in our methodology involved the collection of relevant data, including gridded meteorological forcing data, observational discharge data, glacier mass balance data, and snow water equivalent data. These data sources provide essential information for the modeling process.

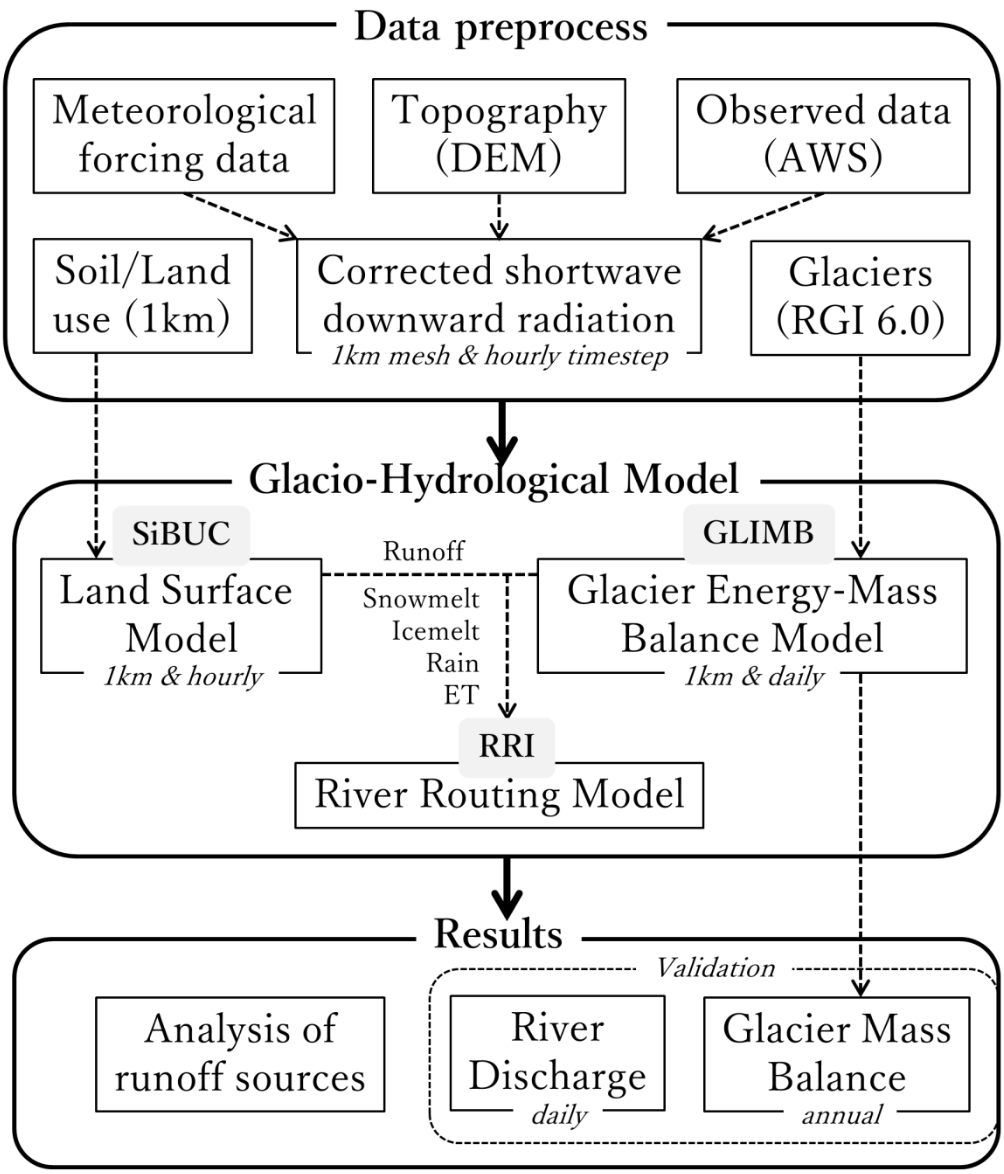

Figure 1.4: Flowchart of the study.

To account for local topographic influences on solar radiation and cloud transmissivity processes, we downscaled the gridded meteorological forcing data. This downscaled data is crucial for improving the accuracy of our model simulations, as it captures the local conditions more accurately.

Next, we selected and integrated suitable land surface, glacier energy-mass balance, and river routing models into a cohesive framework. These models are known for their ability to accurately describe natural processes in mountainous regions, although they require extensive datasets for precise results (Finger et al., 2011).

Using the downscaled meteorological data and the integrated models, we conducted model simulations to simulate the hydrological processes and quantify the contributions of various runoff sources in the glaciated basins. The simulations were based on the specific input data and parameters relevant to the study area.

To assess the accuracy and reliability of our modeling framework, we compared the model simulations against observational data, including discharge, glacier mass balance, and snow water equivalent. This step allows us to validate our models and ensure that they accurately represent the real-world hydrological dynamics in the study area.

Through rigorous analysis and interpretation of the model simulations and observational data, we aim to gain insights into the hydrological processes in glaciated mountain basins and understand the role of various factors in influencing runoff. Furthermore, we will compare our findings with previous studies conducted in the Tien-Shan Mountains to contribute to the existing knowledge on runoff contributions in the study area.

Overall, our research methodology combines data collection, downscaled meteorological data, integrated modeling, model simulations, and model evaluation to provide a comprehensive understanding of the hydrological processes and quantify the contributions of various runoff sources in glaciated mountain basins. This integrated approach ensures the accuracy and reliability of our findings and contributes to the field of water resource management and climate change adaptation in data-scarce high mountain regions.

1.7 Structure of the Thesis

Chapter 1: Introduction

In this chapter, the importance of accurately quantifying runoff sources and hydrological processes in glaciated mountain basins under climate change is highlighted. The impact of climate change on mountainous regions, including rising temperatures, shrinking glaciers, and altered precipitation patterns, is discussed. The need to understand the processes occurring in mountainous areas and define runoff sources, particularly glacial runoff, is emphasized. The chapter also mentions the challenges associated with incorporating radiation data and glaciological models in hydrological modeling, and the significance of downscaled radiation data for glacier melt estimation and overall runoff.

Chapter 2: Literature Review

This chapter provides a comprehensive review of previous studies conducted in the Tien-Shan Mountains and other mountainous regions. The importance of glacial runoff in different basins is discussed, highlighting the varying contributions of glaciers, snowmelt, and rainfall. The use of temperature-index models and energy-balance approaches for glacio-hydrological modeling is examined, along with their advantages and limitations. The decline of the meteorological observation network in Kyrgyzstan after the collapse of the Soviet Union is also mentioned, emphasizing the need for physically based models that rely on fundamental physical principles.

Chapter 3: Methodology

The methodology chapter outlines the approach used in this study to determine the runoff components of glaciated basins in the inner Tien-Shan. A land surface model SiBUC integrated with a glaciological model GLIMB is employed. Gridded reanalysis meteorological forcing data are used, and topographic downscaling of incoming solar radiation is performed to accurately represent high mountain conditions. The chapter also mentions the comparison of model results with observed data, including discharge, glacier mass balance, and Snow Water Equivalent (SWE), to validate the performance of the integrated model.

Chapter 4: Results and Discussion

In this chapter, the results of the model simulations and their implications are presented. The peak glacier melt contribution is found to occur in July and August, with some basins reaching up to 54%. On an annual basis, glaciers contribute an average of 19% to the basins, while snowmelt and rainfall contribute 58% and 23%, respectively. The accuracy of the simulations is assessed by comparing them with observational data, and the role of various factors in influencing runoff is discussed. The chapter highlights the utility of integrated modeling for understanding hydrological processes in data-scarce high mountain regions.

Chapter 5: Conclusion and Future Directions

The final chapter summarizes the key findings of the study and their implications. The integrated modeling approach used in this research has provided valuable insights into the hydrological dynamics of glaciated basins in the inner Tien-Shan. The accurate quantification of runoff components, particularly glacial runoff, is crucial for water resource management under climate change. The limitations and challenges faced in this study are acknowledged, and recommendations for future research, such as improving the representation of glacier dynamics in hydrological models and expanding the observation network, are provided. Overall, this research contributes to the understanding and management of water resources in high mountain regions.

Chapter 2: Literature Review

2.1 Climate Change Impacts on Mountainous Regions

Climate change has been observed to have profound impacts on mountainous regions, affecting various environmental, hydrological, and glaciological processes. Studies have shown that the impacts of climate change in mountainous areas are complex and multifaceted, with implications for glacier melting, water resources, and ecosystem dynamics (Bajracharya & Mool, 2009)Singh et al., 2006). The analysis of climate change impacts in glacierized catchments has revealed that rising temperatures and changing precipitation patterns are leading to a steady decline in glacier area, highlighting the direct influence of climate change on glacier dynamics and hydrological responses (Bajracharya & Mool, 2009). Furthermore, the phenomenon of local atmospheric decoupling in complex topography has been identified as an important consideration in understanding the impacts of climate change in mountainous regions, emphasizing the need to account for local-scale atmospheric processes in climate change assessments (Daly et al., 2009).

The impact of climate change on glacier melting has been a subject of extensive research, with studies indicating that changes in temperature and precipitation are influencing the retreat of glaciers in mountainous regions (Singh et al., 2006). The reduction of water availability during the summer period, which contributes significantly to the annual flow, has been projected to have severe implications for water resources in glacier-fed basins, highlighting the potential consequences of glacier melting on water availability and downstream ecosystems (Singh & Bengtsson, 2004). Additionally, the formation and expansion of moraine-dammed lakes due to rapid glacier melting have raised concerns about the increased risk of glacial lake outburst floods (GLOFs), emphasizing the immediate hazards associated with glacier dynamics in the context of climate change (Bajracharya & Mool, 2009).

Moreover, the impact of climate change on mountainous ecosystems has been a focus of research, with studies indicating that large negative impacts are projected to occur at low and intermediate elevations in initially warm-dry regions, highlighting the vulnerability of mountain ecosystems to relatively small climatic shifts (Elkin et al., 2013). The sensitivity of mountainous regions to climate change has been underscored, with evidence suggesting that mountainous areas are more climatically isolated than previously reported, emphasizing the unique challenges posed by climate change in these regions (Dobrowski & Parks, 2016). Furthermore, the changing characteristics of glaciers in mountainous regions have been studied, revealing significant retreat and changes in glacier area, which are indicative of the direct influence of climate change on glacier dynamics (Gong, 2017).

2.2 Water Resource Management and Climate Change Risk Assessment in Central Asia

Water resource management and climate change risk assessment in Central Asia, including Kyrgyzstan, are critical due to the region's arid climate and heavy reliance on water resources for various sectors. Central Asia is characterized by a complex water management system, and climate change is expected to exacerbate water stress in the region, particularly due to the dependence on glacier meltwater supplied by the Tienshan Mountains, known as the "water tower" of Central Asia (Chen et al., 2017). The quality of water for human consumption is poor in many parts of Central Asia, and the region covers one-third of the arid area of the world, where rivers and lakes are the major sources of surface water resources and supply most of the water for human use in the oases of Central Asia (Lioubimtseva & Henebry, 2009; Bai et al., 2010). The vast majority of the arid lowlands in Central Asia are highly dependent on glacier meltwater, making the region vulnerable to climate change impacts on water availability and downstream ecosystems (Chen et al., 2017).

According to The World Bank report "Adaptation to Climate Change in Central Asia," average temperatures in the region have already risen by 0.5°C, and projections indicate a further increase of 1.6-2.6°C by 2030-2050 (IPCC AR5, 2014). This rise in temperature has significant implications for the water resources system. For instance, the earlier snowmelt caused by rising temperatures will result in peak river flows during the spring, reducing the water discharge available for irrigation by almost 25% (Huss et al., 2018). Although there is currently an increase in runoff volumes due to rapid glacier melting, forecasts suggest that after 2050, the volume of runoff will decrease sharply (Farinotti, 2015).

The cumulative effects of climate change, coupled with the near-complete depletion of the Aral Sea, have exacerbated water scarcity in the region. This scarcity has far-reaching consequences for various sectors of the economy that are crucial for the region's growth and development. Industries such as energy, agriculture, and disaster risk management systems are particularly vulnerable. It is estimated that the cost of natural disasters caused by meteorological events in Central Asia amounts to approximately 1% of GDP per year, and these events have transboundary implications (Third National Communication of the Kyrgyz Republic under the UN Framework Convention on Climate Change, 2016). Therefore, it is crucial to develop an adaptation plan to address these consequences and ensure sustainable development.

The Aral Sea, once considered the fourth-largest lake in the world, has suffered a significant decline in water volume and surface area. Located in the midst of Central Asian deserts, its level has dropped by approximately 20 meters since the 1960s due to reduced water inflow from the Amu Darya and Syr Darya rivers. Today, the Aral Sea contains only around one-tenth of its former water volume, with its surface area shrinking by over 70% (fig. 3).

The impact of climate change in Central Asia is particularly pronounced in its mountainous regions, where the coverage of glaciers has decreased by approximately one-third over the past century. Tajikistan and Kyrgyzstan have the largest glacier-covered areas, although glaciers can also be found in Kazakhstan and Uzbekistan. The total glacier area in the region amounts to 27,677 km2, with the Tian-Shan accounting for 15,417 km2 and the Pamir for 12,260 km2. These glaciers store a significant amount of water resources, but they are melting at a rate of 0.6-0.8% per year (Orlovskiy, 2019).

Over the past 50-60 years, the glaciers in the Tian-Shan and Pamir have decreased by 6 to 40% (Farinotti, 2015). The rate of melting is generally higher at lower altitudes and in the more humid outer ranges of the Tian-Shan, while the eastern ranges experience a lower rate of ice mass loss. Notably, the glaciers in the Northern Tian-Shan, situated in Kazakhstan, are melting at an unusually high rate, with an annual amplitude of ice mass loss ranging from 0.36 to 0.75%.

The melting of glaciers, disappearance of permafrost zones, and reduction in snow cover are projected to diminish the water resources of Central Asia. Additionally, the region is expected to face more frequent natural disasters, such as droughts, heatwaves, floods, landslides, mudslides, and avalanches, due to higher temperatures and intensified precipitation. Floods, in particular, are a common occurrence throughout Central Asia, accounting for 48% of all recorded natural disasters between 1990 and 2011. These floods are primarily caused by heavy and prolonged rainfall, melting snow cover and glacial mass in mountainous areas, and the breaching of glacial lakes. In the past decade alone, over 2,500 people have lost their lives to natural disasters, and approximately 5.5 million people, equivalent to 10% of the region's population, have been affected by the adverse impacts of these events (Ministry of Emergency Situations of Kyrgyzstan, 2014).

Maintaining the current water policy in the face of water scarcity and climate change can significantly impede economic growth in Central Asia. However, there is an opportunity to mitigate these challenges by improving the efficiency of water use in the economy. Enhancing water management practices can contribute to the expansion of agricultural production, the development of "green" energy sources, and the preservation of the region's environmental assets. It is important to note that changing water use patterns will have the most significant impact on economic growth in Central Asia. Mismanagement of water resources will only amplify the consequences of climate change, underscoring the urgent need for effective water resource management strategies in the region.

The impact of climate change on water resources in Central Asia has been a subject of extensive research, with studies indicating that the region is facing future climate-related challenges, particularly in terms of water stress and water-energy resource management (Siegfried et al., 2011; Guo et al., 2016). The vast majority of the arid lowlands in Central Asia are highly dependent on glacier meltwater supplied by the Tienshan Mountains, which are known as the "water tower" of Central Asia (Chen et al., 2017). Additionally, the region's water problems are complex, requiring integrated assessment and management approaches to address the challenges posed by climate change (Karthe et al., 2017). The Central Asia water sector is especially vulnerable to climate change impacts, and there is not yet sufficient local capacity to adequately deal with the present and upcoming challenges (Marti et al., 2022).

In Kyrgyzstan, a country located in Central Asia, the vulnerability of agricultural systems to drought has been assessed, highlighting the impact of the dry climate and frequent droughts on the country's water resources and agricultural sector (Li et al., 2021). The country suffers from a dry climate and frequent droughts, emphasizing the need for effective water resource management and adaptation strategies to address the challenges posed by climate change (Li et al., 2021). Furthermore, the region's water management system is especially vulnerable to suffer from climate change impacts, and there is not yet sufficient local capacity to adequately deal with the present and upcoming challenges (Marti et al., 2022).

2.3 Hydrological Models for Runoff Source Determination

Hydrological models play a crucial role in determining runoff sources in glaciated watersheds, particularly in the context of climate change impacts. The use of distributed and process-oriented hydrological models has been highlighted as a powerful tool for understanding the process dynamics that control the distributed generation of runoff from the river basin landscape, especially in glacierized catchments. These models offer the capability to simulate the hydrological response to climate change in glacierized catchments, providing insights into the impacts of rising temperatures on hydrological processes and the associated generation of water resources (Nepal et al., 2014; Hagg et al., 2007). The J2000 hydrological model has been utilized to understand the hydrological system dynamics of glaciated catchments, such as the Dudh Kosi River basin in Nepal, and to assess the potential effects of rising air temperatures on hydrological processes (Nepal et al., 2013).

The Spatial Processes in HYdrology (SPHY) model has been integrated with relevant hydrological processes, such as rainfall-runoff processes, cryosphere processes, and evapotranspiration processes, to simulate the changes in hydrological processes in glaciated watersheds (Terink et al., 2015). Additionally, the hydrological modeling system PREVAH, which relies on the concept of hydrological response units (HRUs) and incorporates combined temperature-radiation modules for snow and ice melt, has been used to relate climate change signals and physiographic catchment properties to clustered hydrological response types in glaciated watersheds (Köplin et al., 2012).

The response of runoff components and glacier mass balance to climate change in glaciated high-mountainous catchments has been studied, with the temperature-index method frequently incorporated into hydrological models to calculate runoff in glacierized catchments (Wang et al., 2020). Furthermore, the use of the Hydrologic Simulation Program-FORTRAN (HSPF) has enabled the hydrological modeling of glaciated watersheds, providing insights into the runoff simulation and the quantification of the runoff portion of the hydrograph (Srinivasan et al., 1998). An energy-balance numerical model has been employed to discuss the characteristics and sensitivities of glacier runoff, emphasizing the importance of considering the timing of dust events on glacier runoff in glaciated watersheds (Fujita, 2006).

A meta-analysis review of glacio-hydrological studies estimated that about 94% used the temperature-index method for modeling purposes, and only 6% used the energy-balance approach (He et al., 2021). One of the reasons for the widespread use of temperature-index and degree-day models is their requirement for relatively minimal input data, which makes them practical and accessible for various applications (Hock, 2003; Martinec and Rango, 1986). Indeed, in high mountainous areas, establishing an observation network with a broad spectrum of measurements is labour-intensive, and in most cases, air temperature is the only available data metric (Figure 2.1). After the collapse of the Soviet Union, the meteorological observation network declined in Kyrgyzstan, especially in high-altitude areas (Hoelzle et al., 2017). An advantage of physical-based models is that they are based on fundamental physical principles, such as conservation of mass and energy, allowing for a more robust and accurate representation of the modeled system. This approach can lead to a better understanding of the underlying physical processes and improve projections for future scenarios.

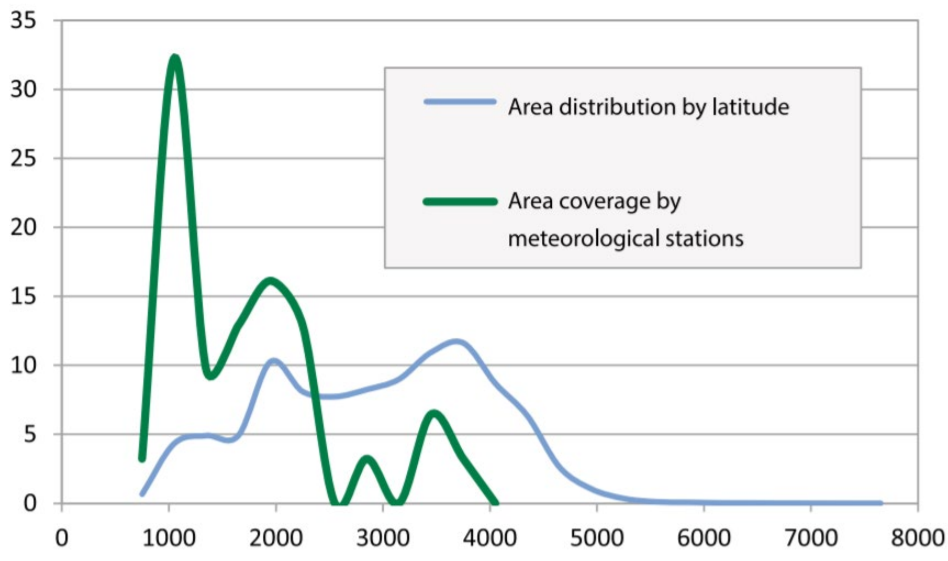

Figure 2.1: Elevation distribution of meteorological stations in Kyrgyzstan (UN, 2016)

2.4 Incorporating Radiation Data in Glacier Melt Estimation

Incorporating radiation data in glacier melt estimation is crucial for understanding the energy balance and melt processes in glaciated watersheds. Studies have shown that solar radiation plays a significant role in influencing glacier mass loss and melt processes. For instance, an inner Alpine radiation record revealed that enhanced solar radiation in the 1940s favored rapid glacier mass loss, indicating the importance of solar radiation in influencing glacier melt Huss et al. (2009). Additionally, the validation of radiation schemes for low-latitude glaciers has demonstrated the satisfactory performance of radiation data in mass-balance modeling, emphasizing the significance of radiation data in understanding the energy balance of glaciers (Mölg et al., 2009).

Furthermore, the spatial distribution of net shortwave radiation has been studied to understand the energy and mass balance of glaciers, revealing the complex effects of shading, slope, aspect, and reflection on net shortwave radiation, which influences the spatial evolution of melt rates in glaciated watersheds (Klok & Oerlemans, 2002). Distributed mass-balance modeling has been improved by incorporating shortwave solar radiation to account for the spatial and temporal variability of melt energy, highlighting the importance of radiation data in enhancing the accuracy of mass-balance models for glaciers (Carturan et al., 2012). Moreover, net radiation has been identified as the dominant source of melt energy in most glaciers, emphasizing the significant contribution of radiation to the energy balance and melt processes in glaciated watersheds (Giesen et al., 2014).

The influence of solar radiation on glacier melt has been further emphasized by the development of linear regression models that use absorbed radiation and temperature to estimate melt, providing insights into the role of radiation in predicting glacier melt (Bash & Moorman, 2020). Additionally, the relative contribution of solar radiation and temperature in enhanced temperature-index melt models has been studied, demonstrating the transferability of radiation-based melt models.

2.5 Challenges in Physically Based Hydrological Modeling

Physically based hydrological modeling encounters several challenges that affect its ability to accurately represent hydrological processes. These challenges have been highlighted in various studies, emphasizing the need for advancements in modeling approaches to address these issues. For instance, (Kirchner, 2006) suggests the need for new data networks, field observations, and field experiments that explicitly recognize the spatial and temporal heterogeneity of hydrologic processes. Additionally, the replacement of linear, additive "black box" models with "gray box" approaches has been proposed to better capture the nonlinear and non-additive character of hydrologic systems (Kirchner, 2006).

Mcdonnell et al. (2007) point out unresolved issues with the current generation of physically based distributed models, arising from the fact that their theoretical foundation is still small‐scale physics or theories. This highlights the need for a more comprehensive understanding of the theoretical foundation of hydrological models to address the challenges associated with process complexity and heterogeneity (McDonnell et al., 2007).

Another challenge in physically based hydrological modeling is the estimation of uncertain flow and transport parameters. Abbaspour et al. (2004) emphasize that inversely obtained hydrologic parameters are always uncertain due to errors associated with measurements, posing new challenges in model parameterization and uncertainty analysis (Abbaspour et al., 2004).

Furthermore, Beven (2001) discusses the challenge of equifinality in distributed hydrological modeling, emphasizing the need to reject models that cannot be considered as physically feasible and to develop ways to test models more comprehensively and incisively (Beven, 2001). This highlights the need for improved model evaluation and selection processes to ensure the physical realism of hydrological models.

2.6 Previous Studies in the Tien-Shan Mountains

Previous studies in the Tien-Shan Mountains have shown the importance of glacial runoff for all basins. In the Northern Tien-Shan, its contribution to the river flow ranged from 18-28% and peaked at 40-70% during summertime, as calculated by temperature-index model (Aizen et al., 1996). By end-member mixing analysis, the ratio of glacier meltwater contribution to the total runoff in Central Tien-Shan and Northern Tien-Shan have been estimated as 42% and 36%, respectively (Chen et al., 2019). In the Tarim basin, the contribution of icemelt, snowmelt and rainfall were evaluated as 44, 28 and 29% for the Kumalike River and 23, 26 and 51% for the Toxkan River, respectively, using enhanced Variable Infiltration Capacity (VIC) model (Zhao et al., 2013). Although it is still challenging to assess runoff contribution with high temporal and spatial scales, distributed models may contribute to understanding the future change of snow and glacier melt dynamics (Unger-Shayesteh et al., 2013).

Hydrological response to climate change in glacierized catchments of the Tien-Shan Mountains has been studied using runoff models such as HBV-ETH and OEZ, providing insights into the temporal and spatial variability of runoff components (Hagg et al., 2007). Furthermore, Kutuzov & Shahgedanova (2009) presented a comprehensive assessment of fluctuations in the extent of glaciers over the past 150 years in the eastern Terskey-Alatoo Range and neighboring glaciated massifs in the inner Tien-Shan, shedding light on the changes in runoff components associated with glacier retreat.

Chapter 3: Research Methodology

3.1 Study Area Description

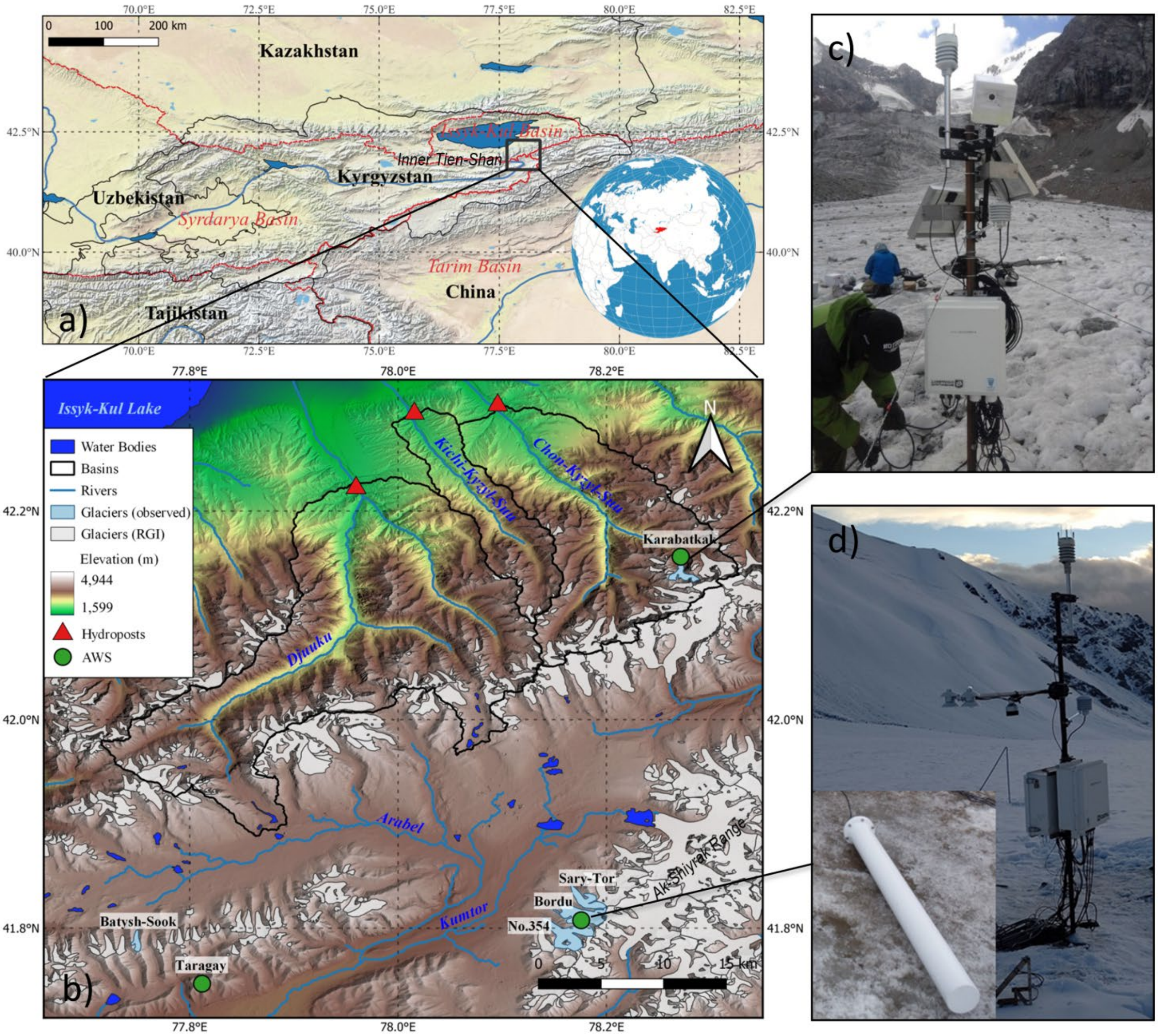

Figure 3.1: Study area map. a) Country and large basin map, b) regional map of studied glaciers and catchments, c) automatic weather station (AWS) on Kara-Batkak Glacier, and d) AWS on Bordu Glacier with an instrument for snow water equivalent (SnowFox).

The study area of this research is focused on the glaciers in Kyrgyzstan, particularly in the inner Tien-Shan and Ak-Shiyrak range. These areas are significant as they serve as the origins of the rivers in the Syrdarya basin, the headwaters of the Tarim basin, and the rivers that flow into the closed endorheic Lake Issyk-Kul (Figure 3.1). According to Dyurgerov (2010), there has been a notable decrease in the area of glaciation in the Tien-Shan mountain system over the period from 1960 to 2006, amounting to nearly 17%. This decline in glacial coverage highlights the need for further investigation into the factors contributing to this change and its implications for the surrounding region.

The study also focuses on the specific basins of the Chon-Kyzyl-Suu, Kichi-Kyzyl-Suu, and Djuuku rivers, which are situated on the northern slope of Terskey Ala-Too and flow into Lake Issyk-Kul. This area is of particular interest due to its vulnerability to climate variability and the potential impacts it may have on the region. Understanding variations in rainfall patterns is crucial for effective water resource planning and management within the Lake Issyk-Kul basin (Alifujiang et al., 2020). Accurate characterization of these variations will provide valuable insights into the availability and distribution of water resources, which are essential for sustainable development and the well-being of the local communities.

Table 3.1: Summary of study catchments.

Basin name	Area (km^2)	Elevation range (m)	Glacier area (km^2)	Glaciated ratio (%)
Chon-Kyzyl-Suu	298	1962 — 4767	32.5	11
Kichi-Kyzyl-Suu	99	1974 — 4707	1.8	2
Djuuku	558	1942 — 4347	44.6	8

3.1.1 Issyk-Kul Lake Basin

The catchment of Issyk-Kul, located at an elevation of 1607 meters above sea level, represents a typical High Mountainous Watershed of Tian-Shan, often referred to as the Northern Himalaya. This region is characterized by its unique natural features, including an endorheic lake and a mountainous landscape, which provide an excellent opportunity to assess the impact of climate change on glaciers and mountainous systems in Central Asia.

Issyk-Kul is the largest lake in Kyrgyzstan and one of the largest high-mountain lakes globally. It boasts magnificent scenery and is renowned for its uniqueness. The lake has a water volume of 1738 km3, a water surface area of 6236 km2, and a coastline length of 688 km. With an average depth of 278 meters and a maximum depth of 702 meters, it ranks as the sixth deepest lake in the world (Klerkx, 2002). Its dimensions span 182 km from west to east and 58 km from south to north.

Situated in the northeastern part of the country, Issyk-Kul is flanked by the Northern Tian-Shan ranges, specifically the Kyungei Ala-Too and Terskey Ala-Too. The lake is characterized by its endorheic nature, meaning it has no outlet, directly connecting fluctuations in its surface to the hydrological processes occurring within the catchment.

Moreover, the sheer size of the lake has a regional-scale impact on the climate.

The foothills of the Kyungei Ala-Too and Terskey Ala-Too consist of Meso-Cenozoic sediments, which have been significantly dissected by ravines and river valleys. The Kyungei Ala-Too ridge spans a length of 280 km, with its crest situated at an elevation of 3,800-4,000 meters. Mount Choktal stands as the highest point, reaching 4,771 meters. This ridge's central part lies above the snow line, hosting small snowfields and glaciers. On the other hand, the Terskey Ala-Too range stretches for 350 km, with its highest section located in the headwaters of the Ak-Suu and Kara-Kel rivers, housing numerous concentrated glaciers. However, it is important to note that the southern slope of the Terskey Ala-Too lies outside the Issyk-Kul catchment.

The climate within the Issyk-Kul Lake catchment is strongly influenced by the presence of the non-freezing lake, resulting in a climate that exhibits characteristics of a marine climate. This includes mild winters, relatively warm summers, and smooth annual variations in air temperature. Within the Issyk-Kul basin, there is a semblance of cyclonic circulation, occasionally disrupted by the inflow of cold air from the east and west. This interaction gives rise to local winds, with the west wind known as "Ulan" being particularly strong, reaching speeds of 25-30 m/s (Revyakin, 1988).

The basin encompasses various climatic zones, including deserts, semi-deserts, steppes, meadow-steppes, forests, subalpine, and alpine zones. This diversity of natural conditions is reflected in the region's vegetation. The basin can be divided into two sub-areas: the western part, which is arid and warm, and the eastern part, which is more humid. The western sub-area is the driest region in Kyrgyzstan, characterized by a semi-desert climate. Annual precipitation ranges from 100-120 mm, with the highest amount occurring in July-August and the lowest in January. Winters in this area experience minimal snowfall, and continuous snow cover is scarce. The average annual air temperature is around 7-8º Celsius. As we move eastward, the amount of precipitation increases.

The central part of the basin's coasts receive 250-350 mm of precipitation, while the eastern coast receives 400-600 mm. The precipitation further increases to 850 mm towards the easternmost point of the basin (Shabunin, 2002). The peak of precipitation occurs in July-August, while the minimum is observed in January-February. In the central part of the southern coast, the average height of snow cover is 2 cm, with a maximum of 12 cm. On the northern coast, the average height is 3 cm, with a maximum of 23 cm. In the eastern part of the basin, snow cover becomes stable from late November, reaching heights of 25-30 cm in the coastal zone and 60-80 cm at an altitude of 2500 m above sea level (Hydrometeorological Agency of Kyrgyzstan, 2018). The average annual air temperature in this region ranges from 6-8°C.

3.1.2. Chon-Kyzyl-Suu River Basin and Karabatkak Glacier.

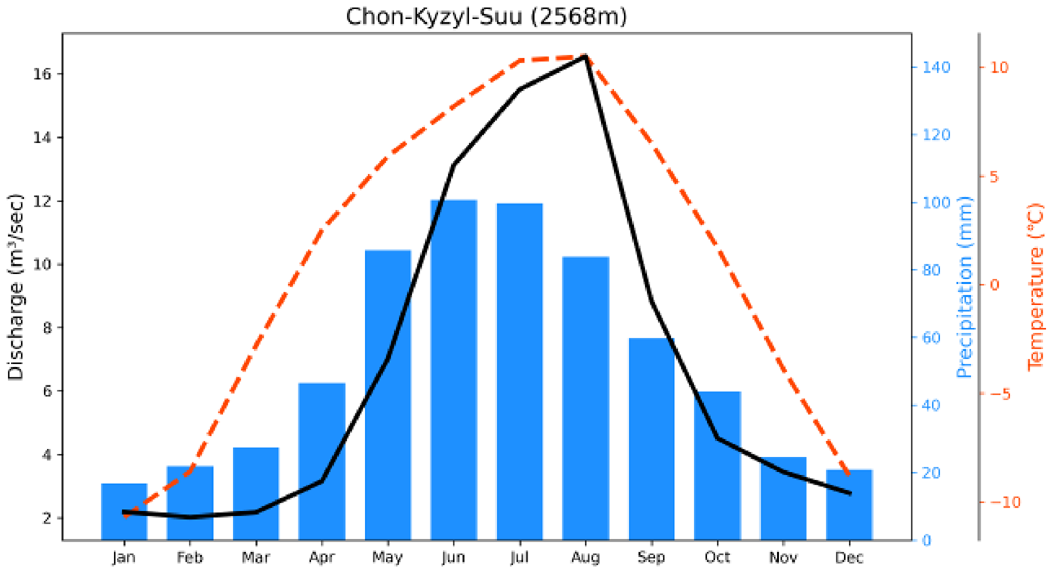

Figure 3.2: Monthly climatology and hydrograph in Chon-Kyzyl-Suu Basin (2002-2020).

The study area includes the Chon-Kyzyl-Suu river basin, where instrumental meteorological and glaciological monitoring has been conducted since the 1950s. However, some data has a particular gap in the 1990s, and observations have been resumed after 2007 (Satylkanov, 2021). The Tien-Shan High Mountain Scientific Center of the Academy of Sciences of Kyrgyzstan monitors Kara-Batkak glacier located in the Chon-Kyzyl-Suu river basin (Figure 3.4). The analysis of hydrographs has been used to identify the contribution of ice melt to the total runoff during the peak discharge and maximum glacier melting period in summer. The results have indicated that the glacier components in highly glaciated basins can account for up to 50% of the total runoff during the ablation period, while snow and rain contribute around 5% (Dikikh, 1991).

Figure 3.3: Photo of observations (snow, temperature, discharge, ablation) on Karabatkak glacier

Figure 3.4: Photo of Karabatkak glacier area

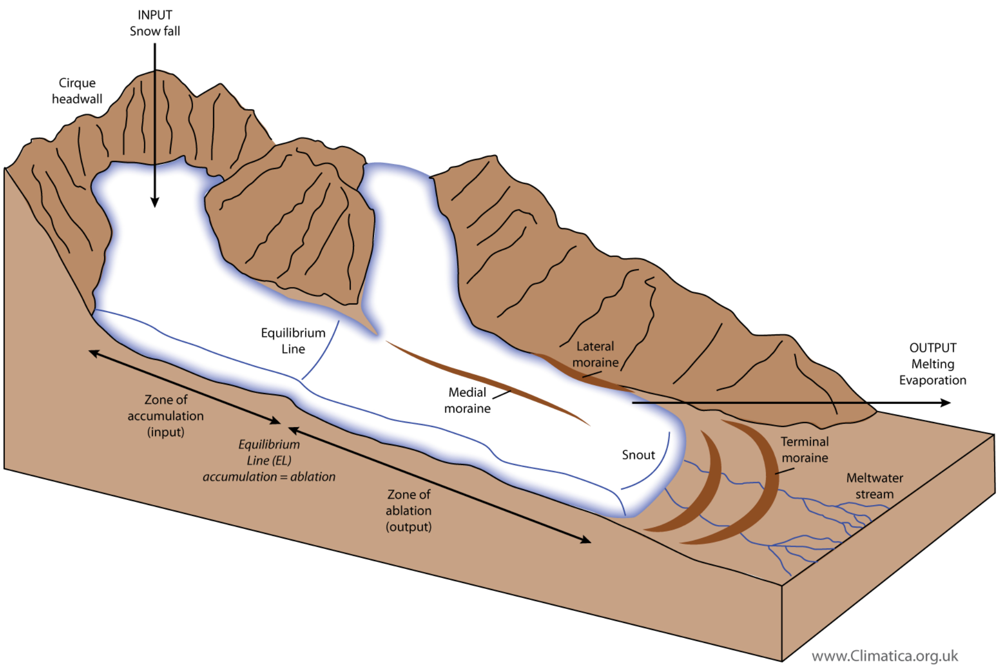

Figure 3.5: A glacier components (L. Sven, 2014)

Calculating the mass balance of a glacier involves assessing the difference between accumulated and melted water content on the glacier (Figure 3.5). Understanding the relationship between mass balance processes and glacier runoff is crucial. However, due to data scarcity and limited accessibility to study objects, it is not possible to cover the entire glaciated area in the basin. Therefore, there may be some uncertainty when generalizing the results from one glacier to the entire basin. To ensure the reliability of such methods, additional validation should be performed.

Data on snow and ice melting from 2008 to 2016 has been obtained from the TShHMRC. Figure 4.3 illustrates the network of measuring points for mass balance components on the Kara-Batkak glacier. The number of stakes on the glacier tongue varied each year, ranging from 12 to 21 in the altitude range of 3300-3500m. In 2015, an additional 13 ablation rods were installed in the upper part of the glacier, including its accumulation zone, at altitudes from 3600 to 4100m. To calculate the mass balance in late spring and early autumn, snow surveys covering the accessible area of the glacier were conducted by probing the seasonal snowpack with metal stakes. The number of probing points varied from 18 to 75 in the feeding area and from 24 to 183 on the tongue, depending on the year. These snow gauging works estimated the volumetric weight, density, and water storage of snow at characteristic points on the surface through the pitting of thickness.

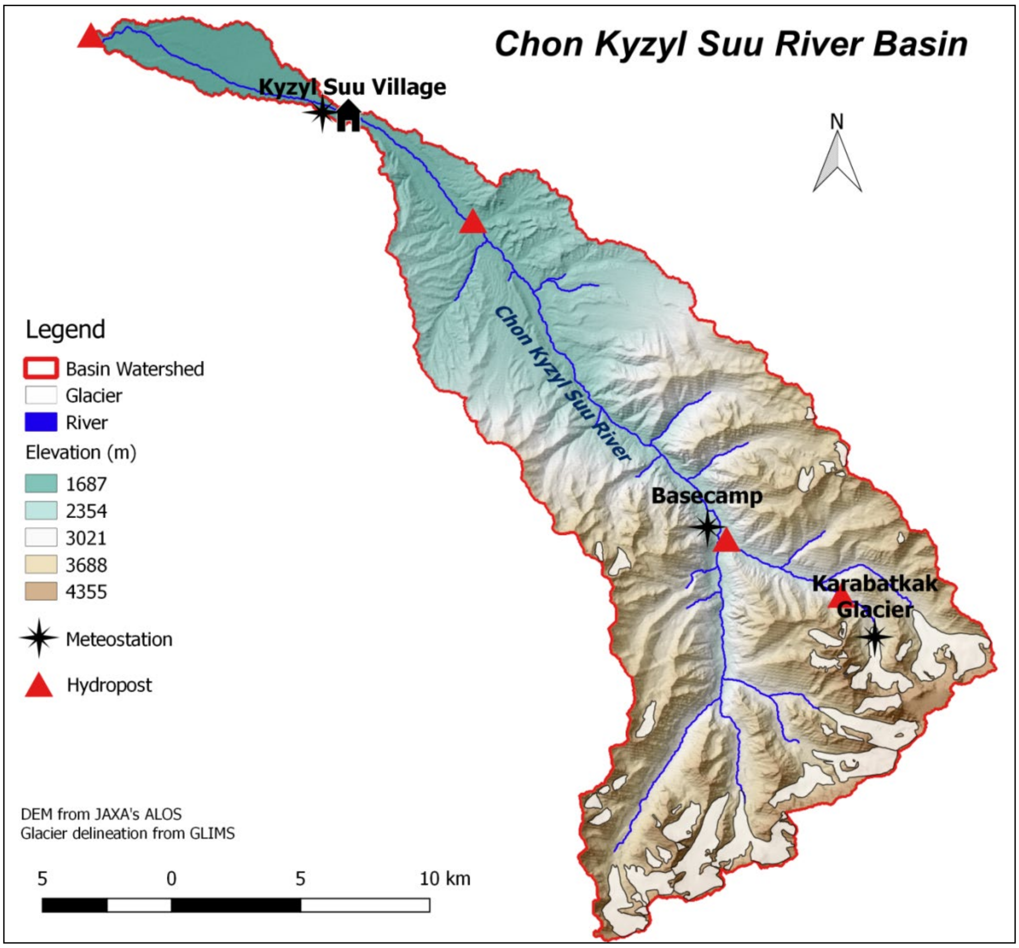

Figure 3.6: Map of Chon-Kyzyl-Suu River Basin

Since July 2017, observations on Kara-Batkak Glacier began with an automatic weather station (AWS). The main components are downward and upward shortwave and longwave solar radiations, measured by Hukseflux NR01 sensor. Temperature, atmospheric pressure, wind speed and humidity are measured by Vaisala WXT536. In August 2018, a similar system has been installed on Bordu Glacier. The data are used to improve the quality of the forcing data for simulations.

The Chon-Kyzyl-Suu river basin has a continental climate with cold winters and warm summers. Monthly temperatures range from an average low of -10.7 °C in January to an average high of 10.5 °C in July (Figure 3.2). Monthly precipitation is highest in the summer, with an average of 100.7 mm in July, and lowest in winter, with an average of 16.9 mm in January. Monthly discharges are lowest in winter, with an average of 2.18 m^3/s in January and highest in summer with an average of 16.55 m^3/s in July.

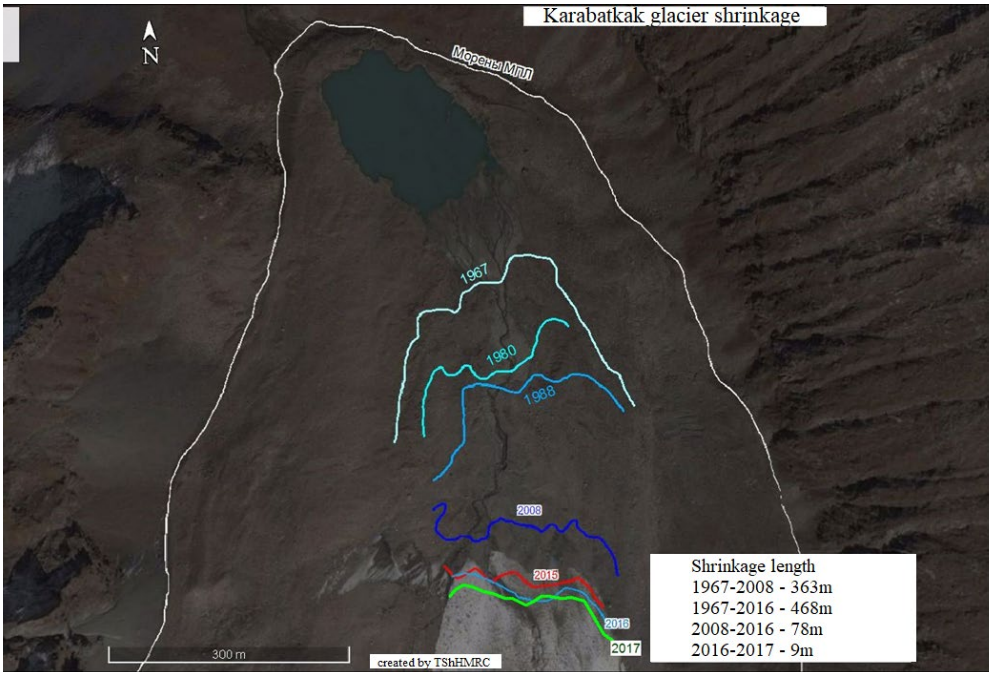

Figure 3.7: Schematic shrinkage of Karabatkak glacier

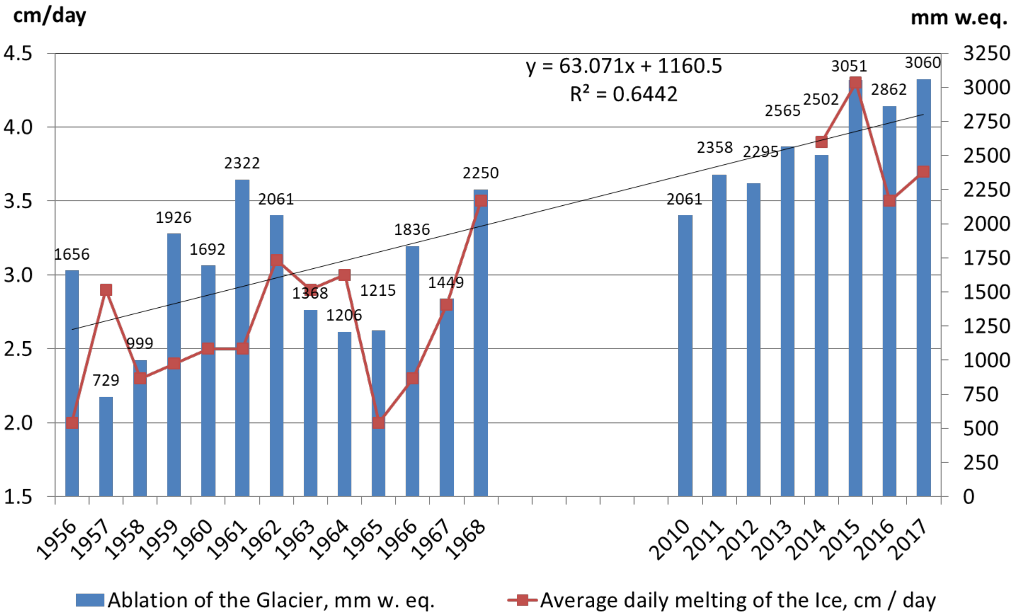

Figure 3.8: Ablation of Karabatkak glacier (Source: TShHMRC)

High mountain regions, where most glaciers are located, are often understudied due to their severe environmental conditions and remoteness. These areas are characterised by extreme weather, difficult terrain, and logistical challenges, making it difficult to collect data. As a result, the existing data coverage in these regions is often sparse, leading to uncertainties in model inputs and potential limitations in accurately simulating the complex processes involved in glaciated basins. Gridded reanalysis meteorological forcing data (Table 3.2) were used for the high mountain conditions of the inner Tien-Shan, which were subsequently validated with the observational data.

3.1.3. Naryn River Basin.

The Naryn River Basin is a significant geographical feature located in Central Asia, spanning parts of Kyrgyzstan, Tajikistan, and Uzbekistan. This basin is characterized by various physical properties that contribute to its hydrological characteristics and overall importance in the region. The Naryn River, the primary river within the basin, originates from the confluence of the Big and Little Naryn Rivers in the Kyrgyz Republic. It flows through mountainous terrain, including the Tien Shan and Pamir-Alai ranges, before entering the Fergana Valley. The length of the Naryn River is 807 km and the basin area is 59000 km^2. The average water flow above the town of Uchkurgan is 480 m^3/s, suspended sediment - 760 kg/s. It is fed by glacial-snow. The flood season is from May to August. Maximum runoff in June-July. It freezes in the upper reaches. Water mineralization is 200-500 mg/l, increasing towards the mouth, especially in low water. In the upper reaches of the river is located Naryn State Reserve with an area of 91023.5 hectares.

The Naryn River Basin is characterized by diverse topography, ranging from high-elevation mountainous areas to low-lying valleys. This topographical variation plays a crucial role in determining the basin's hydrological processes, such as runoff generation, sediment transport, and water storage. The steep slopes and rugged terrain of the mountains contribute to enhanced erosion and sedimentation rates within the basin.

The climate of the Naryn River Basin is predominantly continental, with cold winters and warm summers. This climate pattern influences the hydrological regime of the basin, including precipitation patterns, evaporation rates, and snowmelt dynamics. The basin experiences significant seasonal variations in water availability, with the majority of the annual flow occurring during the spring and early summer due to snowmelt. The Naryn River Basin is also characterized by the presence of numerous tributaries, which contribute to the overall water supply and drainage network. These tributaries originate from glaciers, snowmelt, and springs in the surrounding mountains, providing a continuous flow of water to the main Naryn River. The interaction between the main river and its tributaries affects the basin's overall hydrological balance.

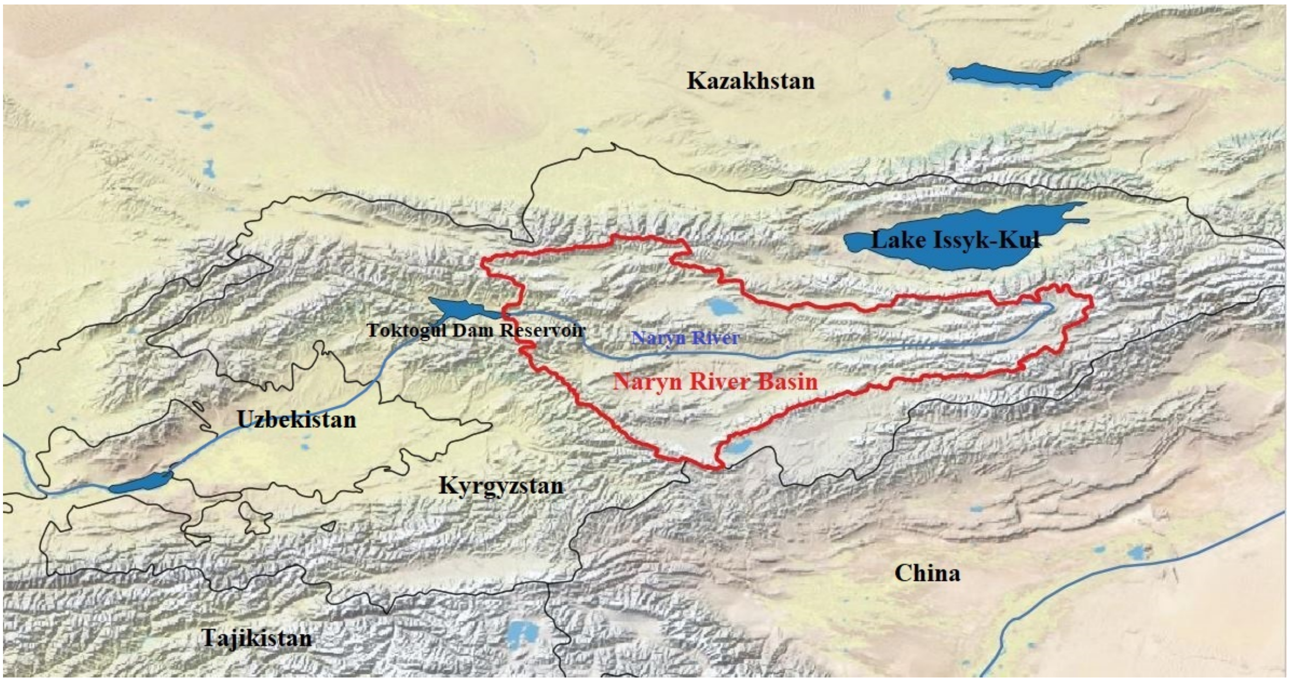

Figure 3.9: Naryn River Basin domain (refer to Figure 3.1a).

The Toktogul Dam Reservoir, located on the Naryn River in Kyrgyzstan (Figure 3.9), plays a pivotal role in electricity generation for the country. With a capacity of 1,200 MW, it is the second-largest hydropower plant in the Aral Sea basin (Bernauer & Siegfried, 2012). The flow of the Naryn River is regulated by the Toktogul Reservoir, which has an active storage capacity of 14 BCM, and it significantly impacts the overall generation of electricity in Kyrgyzstan (Soliev et al., 2015). The reservoir, with a depth of 214 meters, forms a 19.5 - km3 reservoir and intercepts winter water passes, operating in an energy mode (Terekhov & Abayev, 2020). However, the Toktogul dam is designed to resist seismic events of very high magnitude, but the possibility of earthquake-triggered landslides collapsing into the reservoir poses a potential risk (Tibaldi et al., 2018).

The water availability in the Naryn River, regulated by the Toktogul Reservoir, directly affects electricity generation in Kyrgyzstan. The reservoir's capacity to store water and regulate its flow is crucial for maintaining a consistent supply of water for hydropower generation. The ongoing conflict about the management of the Toktogul reservoir highlights its significance as the most important infrastructure for water resource management in the region (Betz et al., 2022). Additionally, the reservoir's impact on ground deformations in response to water level variations underscores its influence on the surrounding environment (Neelmeijer et al., 2018).

Figure 3.10: Toktogul dam (Source: Wikimedia).

Furthermore, the Naryn River, which flows through the Toktogul Reservoir (Figure 3.10), supplies water to the agriculturally important and heavily irrigated Ferghana Valley in Uzbekistan, emphasizing the broader regional implications of water availability in the Naryn River Basin (Wu et al., 2019). The changes in glacier area and volume in the Naryn Basin, where the Toktogul Reservoir is located, have been attributed to increasing summer temperatures, highlighting the interconnectedness of climate change, glaciers, and water resources in the region (Gan et al., 2015). Toktogul Dam Reservoir, as a key component of the Naryn River Basin, significantly influences the overall generation of electricity in Kyrgyzstan. Its regulation of water flow and storage capacity are essential for hydropower generation, and its management and potential risks have broader implications for water resources and regional stability.

3.2 Data Collection and Preprocessing

Data collection begins with obtaining the reanalysis data, which is a combination of observed data and atmospheric model simulations. Reanalysis data provides a comprehensive and consistent dataset covering a long period, typically spanning several decades. This data includes variables such as temperature, precipitation, wind speed, humidity, and other relevant meteorological parameters.

Table 3.2: Meteorological forcing data used in this study.

Variable	Unit	Resolution	Source
Wind speed	m s^{-1}	0.25° x 0.25°, hourly	ERA5 (Hersbach et al., 2020)
Total cloud cover	0 to 1		
SW downward radiation	W m^{-2}		
SW downward radiation, clear-sky	W m^{-2}		
LW downward radiation	W m^{-2}		
Surface pressure	Pa		
2m dewpoint temperature	K		
2m temperature	K		
Precipitation	mm	0.1° x 0.1°, hourly	GPM-IMERG (Huffman et al., 2015)

Abbreviations: SW – shortwave, LW – longwave.

Once the reanalysis data is obtained, it undergoes preprocessing to prepare it for integration into the land surface models. Preprocessing involves several steps:

Spatial and temporal resolution adjustment: Reanalysis data is often available at a global or regional scale with a relatively coarse spatial resolution. To match the scale of the land surface models, the data may need to be interpolated or downscaled to a finer resolution. Similarly, the temporal resolution might need to be adjusted to match the time steps of the land surface models.

Quality control: The collected reanalysis data undergoes rigorous quality control to identify and correct any errors or inconsistencies. This process ensures that the data used in the models is reliable and free from any artifacts that could affect the accuracy of the simulations.

Bias correction: Reanalysis data may have inherent biases, especially when compared to observed data. Bias correction techniques are applied to adjust the reanalysis data to align more closely with the observed data. This step helps to reduce systematic errors and improve the accuracy of the simulations.

Data assimilation: In some cases, additional observed data, such as streamflow or groundwater level measurements, can be assimilated into the reanalysis data to further improve its accuracy. Data assimilation techniques combine the reanalysis data with the observed data using statistical methods or data assimilation algorithms, ensuring that the models reflect the real-world conditions more accurately.

Model-specific preprocessing: Depending on the land surface model being used, additional preprocessing steps may be required to format the reanalysis data in a way that is compatible with the model's input requirements. This may involve converting the data into specific file formats or reorganizing it to match the model's spatial and temporal structure.

Overall, the data collection and preprocessing steps for implementing reanalysis data into land surface models for hydrological modeling are essential for ensuring the reliability and accuracy of the simulations. These steps help to address issues related to spatial and temporal resolution, data quality, bias correction, and assimilation of additional observed data. By carefully preparing the reanalysis data, researchers can generate more robust and meaningful results in their hydrological models.

In the context of data preprocessing for temperature in the implementation of reanalysis data into land surface models, the air temperature is a crucial variable that significantly influences the modeling outcomes, along with solar radiation. In this study, the reanalysis data for 2-meter height temperatures over the ground surface were downscaled based on the elevation grid.

The primary component of the downscaled temperature data is the temperature lapse rate. This value represents the rate at which temperature decreases with increasing elevation and varies significantly in mountainous areas with complex topography (Jobst et al., 2017; Marshall et al., 2007; Minder et al., 2010; Shen et al., 2016). For this study, a commonly used value of 6.0℃ per kilometer was employed. This value represents the average decrease in temperature with each kilometer rise in elevation in mountainous regions.

It is important to note that the temperature lapse rate can vary depending on various factors, such as local topography, atmospheric stability, and regional climate characteristics. However, in the absence of specific observations or site-specific data, using an average value is a practical approach. The chosen lapse rate value of 6.0℃ per kilometer aligns closely with the previously observed temperature lapse rate of 5.8℃ per kilometer in the Tien-Shan mountains (Aizen and Aizen, 1997). This observation provides some validation for the selected value and suggests that it is an appropriate representation for the study area.

By applying the temperature lapse rate to the reanalysis data, the downscaled temperature data can be adjusted to account for the elevation differences across the study area. This adjustment is essential as temperature variations with elevation influence various hydrological processes, such as snowmelt, glacier melting, and evapotranspiration.

Overall, the data preprocessing for temperature involves downscaling the reanalysis data by incorporating the temperature lapse rate. The selected value of 6.0℃ per kilometer, based on previous observations in the Tien-Shan mountains, provides a reasonable estimation of the temperature decrease with increasing elevation. This preprocessing step is crucial for generating accurate and representative temperature data for the land surface models, ensuring more reliable and realistic simulations of hydrological processes in the study area.

3.2.1 Precipitation data

The primary source of moisture in the watershed under study is precipitation, which can occur in both solid and liquid forms. The amount and seasonal distribution of precipitation play a crucial role in determining the runoff of glaciers, as well as surface and subsurface runoff, and their temporal distribution throughout the year. However, the understanding of precipitation patterns in mountainous areas, particularly at high elevations, is limited due to the scarcity of observation data.

The combination of atmospheric circulation and the terrain structure in mountainous regions leads to a unique and complex distribution of precipitation. Different areas within the mountainous terrain, such as slopes, peaks, and valley bottoms, experience variations in heating and cooling, resulting in slope and mountain-valley circulation. This circulation exhibits a diurnal cycle, with differing wind patterns and air movement throughout the day.

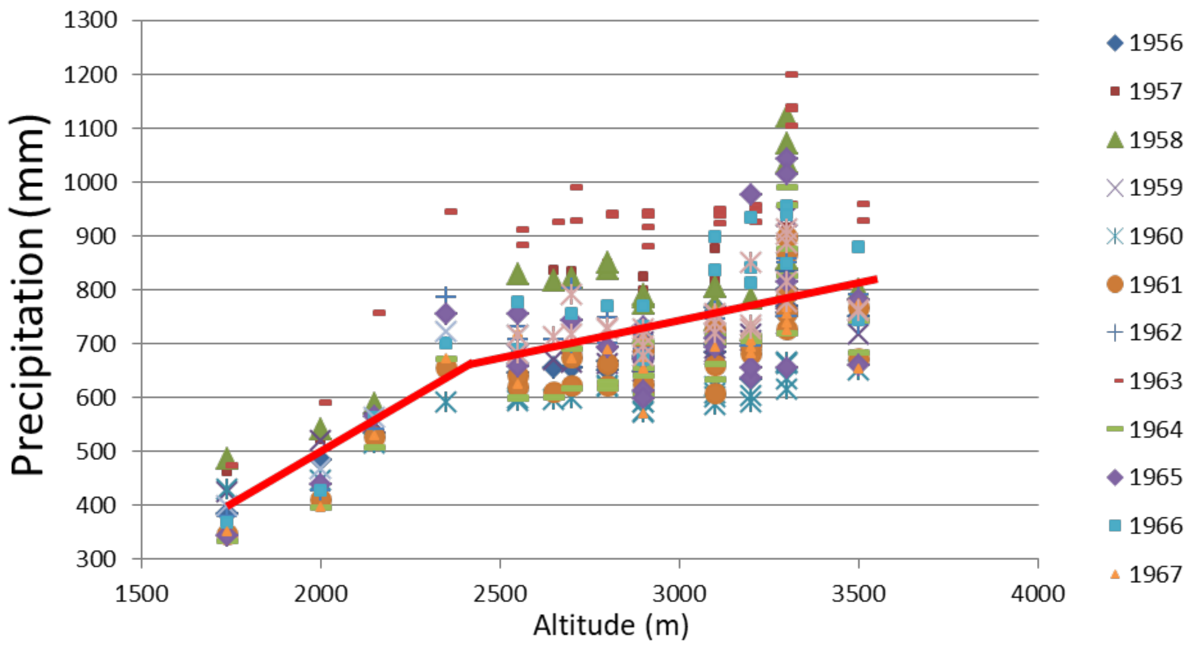

Figure 3.11: Analysis of annual precipitation among 30 stations (1956-1967) in

Chon-Kyzyl-Suu Basin.

As one ascends in elevation, precipitation generally increases. This trend is influenced by atmospheric circulation patterns and the general variations in air temperature. The majority of the water vapor contributing to precipitation is replenished from the air in the foothills and valleys, which receives moisture from evaporation in the Issyk-Kul Lake basin and evaporation from the lower slopes of the mountains.

In terms of precipitation distribution, the share of winter precipitation in the piedmont plain is approximately 15% of the annual precipitation, while in the highlands, it constitutes around 45%. This disparity is attributed to the specific atmospheric circulation conditions and the overall temperature dynamics observed in the region.

The analysis of precipitation data within the studied mountainous river catchment reveals a reasonably good agreement in the total annual precipitation values. Most of the precipitation gauges form a cluster-system, indicating a coordinated and consistent picture of precipitation distribution across the watershed. This implies that the data collected from these gauges can be considered reliable for estimating the total annual precipitation.

In our study, we recognized the importance of using reliable precipitation data for accurate hydrological modeling in mountainous areas. To address this, we employed the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) product, which is known for its suitability in mountainous regions.

The GPM-IMERG product provides precipitation estimates derived from satellite observations, offering a broader spatial coverage compared to traditional rain gauges. However, it is crucial to acknowledge the potential biases and limitations of satellite precipitation products, as they may not accurately capture the precipitation patterns in complex terrains.

However, it is important to note that in certain months, some gauges may exhibit significant deviations from the general pattern of precipitation distribution. This variation highlights the need for caution when relying on data from individual gauges to estimate precipitation amounts. To mitigate this issue, it is recommended to average the values obtained from multiple gauges to obtain a more representative estimation of precipitation (Figure 3.11). By considering data from multiple gauges, a reasonably reliable distribution of the total annual precipitation in the mountainous river catchment can be obtained. This approach helps to minimize the potential biases and uncertainties associated with relying on data from a single gauge.

The relationship between precipitation and altitude is crucial for understanding hydrological processes, especially in mountainous areas. Satellite precipitation products, such as the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG), have been widely used to study precipitation in mountainous regions. However, it is essential to consider the potential biases in these products. Studies have shown significant inconsistencies in bias, false alarm ratio (FAR), and probability of detection (POD) in satellite precipitation products like TRMM, PERSAINN, and CMORPH (Tobin & Bennett, 2010). The accuracy of these products is particularly important for hydrological modeling, where rain gauges and weather radars are commonly used data sources for comparison (Gilewski & Nawalany, 2018). The GPM scientific community acknowledges the need to refine precipitation retrieval algorithms and improve the accuracy of satellite precipitation products, especially in ungauged basins, for flood control and disaster mitigation (Yuan et al., 2019).

In mountainous areas, the altitude can introduce biases in precipitation products. Previous research has evaluated the performance of IMERG at different scales and revealed region-specific biases in representing large-scale monsoon rainfall spatial features (Krishna et al., 2017). Additionally, accurate estimation of precipitation is crucial for various hydrometeorological applications, especially in semi-arid regions, where GPM-IMERG-E precipitation estimates have been found valuable for flood modeling (Saouabe et al., 2020). However, the complex morphology and different precipitation types in mountainous areas, influenced by steep orography and interactions with humid air masses, pose challenges for satellite precipitation products (Caracciolo et al., 2018). Furthermore, the high elevation and complex terrain in mountainous areas make accurate precipitation estimation more difficult (Zhang et al., 2021).

The partitioning of precipitation into rain and snow is a critical aspect of hydrological processes, particularly in mountainous regions. The rain-snow phase transition temperature threshold is a key metric for defining the partitioning of precipitation phase at a given location Jennings et al. (2018). This partitioning has significant implications for water management, as it affects the availability of water for warm-season use (Lynn et al., 2020). Moreover, the altered timing and rate of snow versus rain inputs can modify the partitioning of water to evapotranspiration versus runoff, highlighting the importance of accurate precipitation phase partitioning for understanding hydrological processes (Harpold et al., 2017).

Various methods have been proposed to separate rain and snow based on temperature, and these methods have been evaluated across different climatic gradients. The sensitivity of simulated snow accumulation and melt to rain-snow partitioning methods has been quantified, emphasizing the need for accurate partitioning methods in snow accumulation and melt simulations (Jennings & Molotch, 2019). Additionally, the partitioning of precipitation into rain and snow has been found to have important effects on the hydrological and hydrochemical response of catchments, particularly during rain-on-snow events (MacLean et al., 1995).

3.3 Models used in the study

Land surface and energy balance models are often used as boundary layers in Global Climate Models (GCM) (Cox et al., 1999; Verseghy, 1991), especially when determining the future state of the system. The resolution has a significant impact, particularly in mountainous areas with complex topography. A general description of the modeling methodology involves the introduction of an additional class of glacial component into the mosaic scheme of the land surface gridded model. The land surface model SiBUC was applied to the area to determine the energy and water balance of the area. The glacial energy and mass balance algorithm was carried out separately by the GLIMB model. Combined runoff sources and evaporation from two models were used as inputs for the river routing model (RRI).

3.3.1 Land surface model: SiBUC

Simple Biosphere including the Urban Canopy model (SiBUC)(Figure 3.12) is a land surface model using water-energy balance in the grid system (Tanaka, 2004). Based on the Simple Biosphere model (SiB) (Sellers et al., 1986) and SiB2 (Sellers et al., 1996) models, it utilises processes for several mosaic schemes: green area, water body and urban area. Accounting for additional processes in the mountain environment such as glacier melt in regional simulations can improve the overall understanding of the system (Zhao et al., 2013).

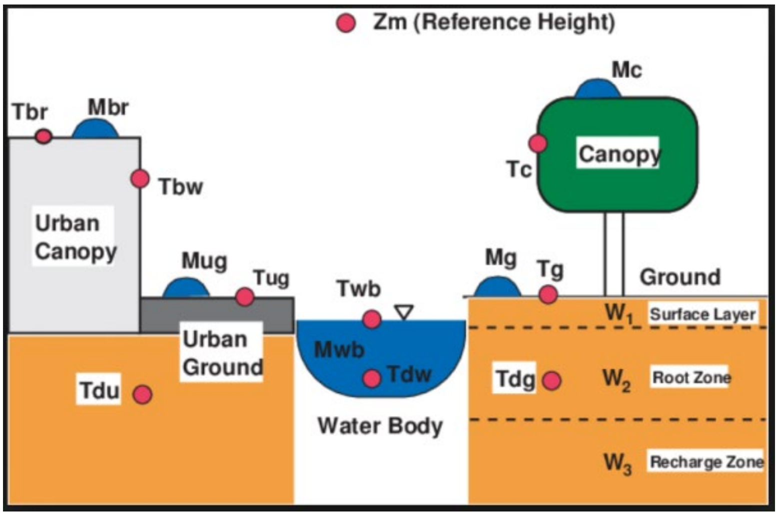

Figure 3.12: Diagram of SiBUC's variables

Table 3.3. Description of SiBUC's variables

green area	M_w interception water stored on building wall
T_c temperature for vegetation canopy	M_{ug} interception water puddled on the road
T_g temperature for soil surface	**water body**
T_d temperature for deep soil in green area (daily mean of T_g)	T_{wb} temperature for water surface
M_c interception water stored on canopy	T_{dw} temperature for deep water (daily mean of T_{wb})
M_g interception water puddled on the ground	**boundary conditions**
W_1 soil moisture wetness for surface layer	z_m reference height m
W_2 soil moisture wetness for root zone	T_m air temperature at z_m K
W_3 soil moisture wetness for recharge layer	e_m vapor pressure at z_m mb
urban area	u_m wind speed at z_m m s−1
T_r temperature for building roof	S ↓ downward shortwave radiation W m−2
T_w temperature for building wall	L ↓ downward longwave radiation W m−2
T_{ug} temperature for road	P precipitation rate m s−1
T_{du} temperature for deep soil in urban area (daily mean of T_{ug})	
M_r interception water stored on building roof	

Two surface temperatures for canopy and ground (T_c, T_g) are estimated in the green area submodel to determine the surface fluxes. The force-restore model (Deardorff, 1977) describes heat transfer in soil. The analytical solution of the heat conduction equation under periodic forcing is utilised to parameterise the periodic ground heat flux. This allows for a basic and roughly accurate representation of temperature dynamics. However, the prognostic equation for T_c does not include a restoring factor since the heat conduction term during the vegetation stage is negligible. As a result, the governing equations for the three temperatures are represented as follows:

$$C_c \frac{\partial T_c}{\partial t} = Rn_c - H_c - \lambda E_c$$

$$C_g \frac{\partial T_g}{\partial t} = Rn_g - H_g - \lambda E_g - \omega C_g (T_g - T_d)$$

$$C_d \frac{\partial T_d}{\partial t} = Rn_g - H_g - \lambda E_g$$

Where C_c, C_g, C_d are heat capacities respectively for canopy, ground and deep soil. T_d – deep soil temperature, Rn_c, Rn_g – absorbed net radiation, H_c, H_g – sensible heat fluxes, $\lambda E_c, \lambda E_g$ – latent heat fluxes, ω – angular frequency of diurnal cycle (2π/86400). The governing equation for snow temperature is expressed as:

$$C_s \frac{\partial T_s}{\partial t} = Rn_g - H_g - \lambda E_g - K_s \frac{T_s - T_g}{D_s}$$

Where C_s is a heat capacity of the snow, T_s is a snow surface temperature, K_s – snow thermal conductivity and D_s – snow depth. Further explanation of snow routine can be found at Sellers et al. (1996). The linear development of snow cover fraction (SCF) regarding snow water equivalent has been changed to consider rapid establishment of snow cover for a small scale simulations according to Niu and Yang (2007). The snow albedo estimation has been adapted from Kondo and Xu (1997), taking into account the ageing of snow over a certain period of time:

$$a_d = (a_{d-1} - a_f)e^{-\frac{1}{k}} + a_f$$

When a snowfall of more than 5 mm w.e. occurs, the number of days (d) is set to 0, a_f is the albedo of firn. Albedo of fresh snow a_0 and parameter k depends on the air temperature on that day.

3.3.2 Glacier energy-mass balance model: GLIMB

To incorporate glaciological processes into the overall scheme, we used the GLIMB model (Figure 3.13) previously applied to glaciers in the Tibetan region and in the Himalayas (Fujita and Ageta, 2000; Fujita and Sakai, 2014). Glacier surface temperature (T_s) is one of the major factors determining the heat (Q_s) and mass balance of a glacier and is used in the following equation:

$$Q_s = (1 - a_s)H_{SR} + H_{LR} - \varepsilon\sigma(T_s + 273.15)^4 + H_S + H_L - G_g$$

Ice surface albedo (a_s) is a constant mean value of 0.25 derived from AWS on Kara-Batkak and Bordu glaciers. This value coincides substantially with the instrumental albedo value on glacier No.354 located in the Ak-Shyirak range (Petrakov et al., 2019). H_{SR}, H_{LR}, H_S, H_L – are downward shortwave, longwave radiations, sensible and latent heat fluxes, respectively. G_g is a conductive heat flux into the glacier ice determined by changing the ice temperature profile. The turbulent sensible heat flux (H_S) and latent heat flux (H_L) were determined using the bulk aerodynamic method. The gradients of mean horizontal wind speed (U), mean air temperature (T), and mean specific humidity (q) were assumed to be equal to the finite difference between the measurement level and the surface:

$$H_s = \rho C_p U C_s (T - T_s)$$

$$H_L = \rho l_f U C_L (q - q_s)$$

Where ρ represents air density, C_p is the specific heat capacity of air, T_s is the surface temperature, q_s is the specific humidity at the surface, U is the wind speed, l_f denotes the latent heat of evaporation (2.514 × 10^6 J kg^{-1}) or sublimation (2.849 × 10^6 J kg^{-1}), depending on the surface temperature. The bulk exchange coefficients for sensible and latent heat, represented by C_s and C_L respectively, were assumed to be constant (0.002). This choice was made due to the lack of information regarding surface roughness and wind profiles over snow and ice. Glacier runoff (D_g) is calculated as:

$$D_g = \frac{t_{day} Q_s}{l_m} + P_r + \left[\frac{H_L}{l_e}, 0\right] - R_f$$

Where R_f is a refrozen ice in a snow layer, t_{day} is a length of a day in seconds, l_m is a latent heat fusion of ice, P_r is a rainfall in millimetres, l_e is a latent heat of evaporation of water. The distinction of snow (P_s) and rain is assumed as follows:

$$P_s = P_p \qquad [T_a \leq 0.0°\text{C}],$$

$$P_s = (1 - \frac{T_a}{4.0})P_p \qquad [0.0°\text{C} < T_a < 4.0°\text{C}],$$

$$P_s = 0 \qquad [T_a \geq 4.0°\text{C}],$$

$$P_r = P_p - P_s.$$

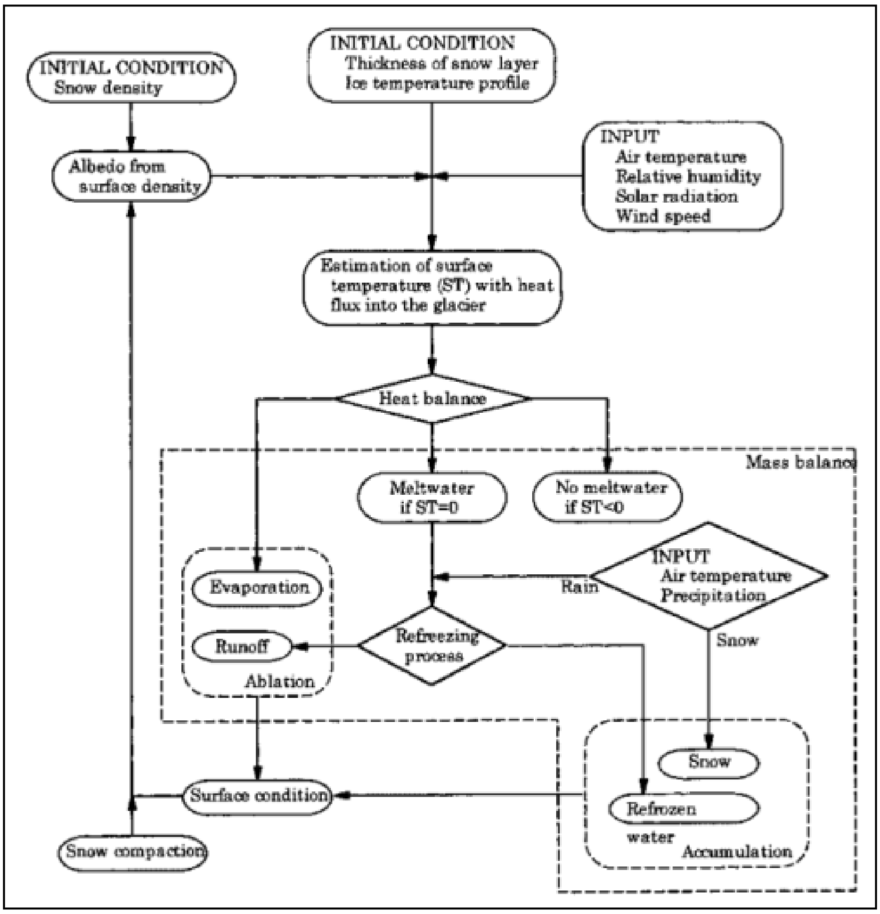

Figure 3.13: Scheme of GLIMB processes (Fujita and Ageta, 2000).

The further explanation of the model can be found in Fujita and Ageta (2000) and Fujita and Sakai (2014). Data from GAMDAM Glacier Inventory (Nuimura et al., 2015; Sakai, 2019), which was incorporated into the global glacier inventory (Randolph Glacier Inventory (RGI) version 6.0, RGI Consortium, 2017), was used to determine the percentage of glaciated mask in the gridded model. Thus, the processes occurring on the glacier surface are determined by GLIMB and on the ground surface by SiBUC.

3.3.3 River runoff model: RRI

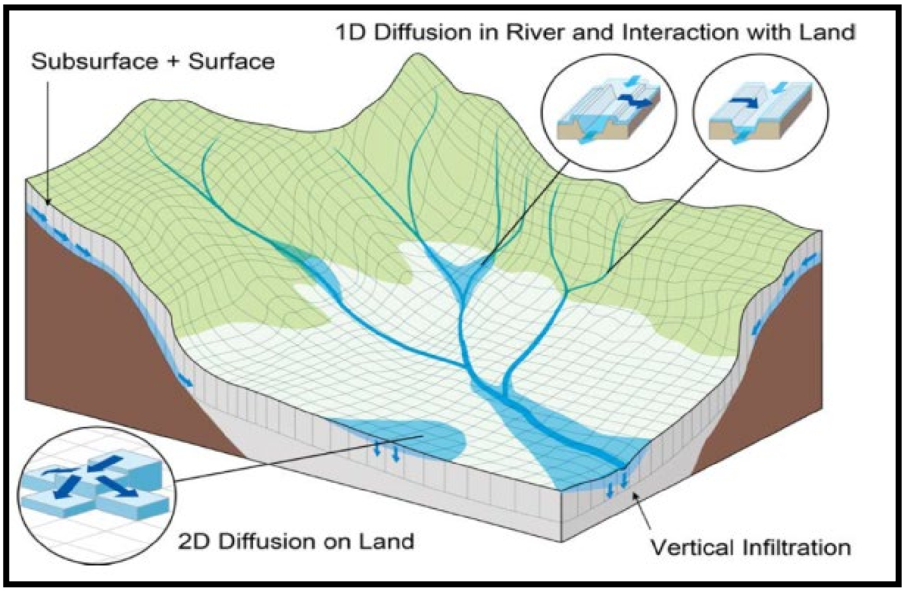

Figure 3.14: Schematic representation of Rainfall-Runoff Inundation Model

The Rainfall Runoff Inundation (RRI) model is a mathematical framework developed by Sayama et al. (2012) to simulate the complex relationships between rainfall, runoff and inundation. The model incorporates a variety of physical processes, such as surface runoff, subsurface flow and overland flow, to accurately simulate the hydrological behaviour of a given terrain. Its primary purpose is to help decision-makers assess the impacts of different hydrological scenarios, such as rainfall intensity and duration, on the potential for flooding. The RRI model is based on a set of equations which are designed to capture the spatial and temporal variability of rainfall, runoff, and inundation within a given area. In addition, the equations consider interactions between different components, such as the amount of infiltration and evaporation and the effects of slope and surface roughness.

Table 3.4: Land type parameters used in RRI.

Land type / Parameter	Highland Permafrost	Lowland Soil
soildepth	2.000d0	7.000d0
ns_slope	3.000d-1	3.000d-1
gammaa	4.750d-1	4.750d-1
ksv	0.000d0	0.000d0
faif	3.163d-1	3.163d-1
ka	1.000d-2	1.000d-3
gammam	0.000d0	0.000d0

beta	8.000d0	8.000d0

In our study, we utilised a land surface and glaciological model in combination with RRI to improve the estimation of hydrological processes within the catchment. The RRI component was used to simulate river flow and consider lateral subsurface flow based on soil parameters (Table 3.4). This was particularly important for accounting for the permeability of the permafrost layer in high mountainous areas. Due to the lack of subsurface data and the limited availability and challenges associated with obtaining geological research, we presumably determined the occurrence of permafrost by elevation according to earlier studies in the Tien-Shan Mountains (Zhao et al., 2010). The land surface model component accounted for processes such as soil and vegetation interception, soil moisture dynamics, and the energy budget, which are crucial for accurately estimating variables such as low-flow conditions, flood onset, peak discharges, and inundation depths. This integrated modeling approach, as highlighted by previous studies (Rasmy et al., 2019), provides a comprehensive framework for capturing the complex dynamics of water flow in mountainous regions.

3.3.4 Temperature-index model

In the field of glacier ablation estimation, there are various methods that can be utilized, each with its own advantages and complexities. Two commonly used approaches are the temperature index model and the more intricate heat balance model. The distributed glacier runoff model is often employed to increase the complexity of heat balance models and their application to a specific model. However, for the purpose of this research, a simpler temperature index model was chosen.

The temperature index model offers the advantage of simplicity, particularly in relation to the tuning of the ablation and temperature relationship. This model relies on the relationship between temperature and ablation, making it more straightforward to implement. Conversely, the heat balance models encompass a wider range of factors and variables, such as shortwave radiation, which can be challenging to consider due to the differing topographic exposure of each glacier and potential errors in the downscaling of forcing data.

For this particular study, a linear regression model was developed using temperature and ablation data from the Karabatkak glacier spanning the years 2008 to 2016. To extend the application of the model to higher elevations, an elevation lapse rate for temperature of 0.6°C/100m was utilized. Additionally, the researchers examined the correlation between cloud conditions and ablation by incorporating cloud coverage data from ERA5.

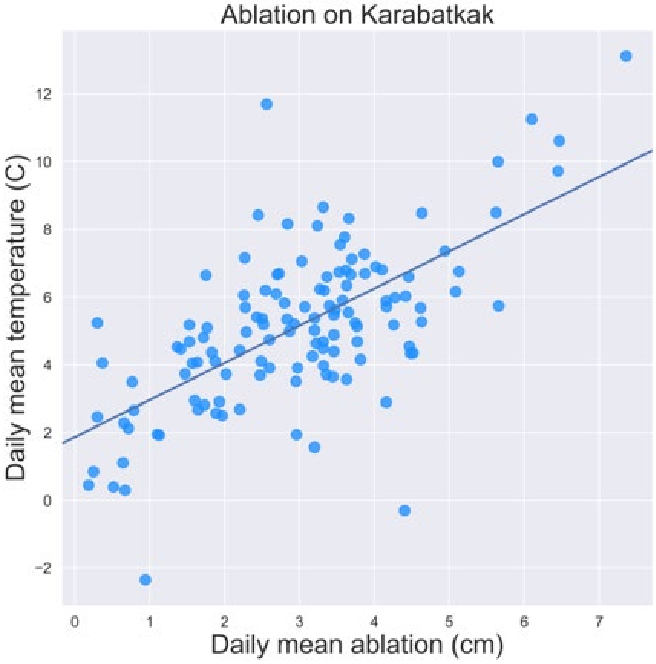

Figure 3.15: Ablation-temperature relationship on Karabatkak glacier

Figure 3.15 in our research indicates that the sensitivity of ablation, or the melting of ice, increases significantly after the daily mean temperature reaches 4°C. This finding is crucial in understanding the limitations of the regression method when applied to hourly time step simulations. It suggests that the model may overestimate melting during periods of high-temperature spikes. This is an important consideration in accurately predicting glacier ablation and its impact on water resources.

To delineate the extension of glaciers, we utilized data from the GLIMS Randolph Glaciers Inventory v6.0 (RGI), as shown in Figure 3.1. The grid resolution for the SiBUC simulation was set to 1km, allowing us to include most of the catchment glaciers within the analysis. However, to improve the accuracy of the glacier mask, we initially set the grid resolution to 100m and calculated the ratio value in percentage for each grid. For example, if 85% of a 1km grid is covered by glaciers, the corresponding value would be 0.85.

The glacier melting algorithm employed in our study requires several conditions to activate runoff. We assumed that ice on the glacier starts to melt once the winter snowpack has disappeared, although some snow may persist at higher elevations. After conducting several trials, we determined that an optimal threshold for snowpack disappearance was set at 5 mm of SWE (snow water equivalent). However, it is worth noting that the SiBUC snow melting routine has a tendency to shift snowpack disappearance to an earlier period, which is a known issue in land surface models (Hiraoka, 2020). Consequently, there may be overestimation of melting in the earlier months, resulting in faster melting of the snowpack in the glacier accumulation zone and, in some cases, complete disappearance during the ablation period.

In our analysis, we divided the glacier into two parts: the zone of accumulation and the ablation zone, with the equilibrium line serving as the dividing point, as depicted in Figure 3.5. From the mass balance measurements, we found that the accumulation zone contributes approximately 5-10% of the total ice melt during the season. To address the issue of overestimation, we opted to neglect melting in the accumulation zone by setting a snowline or Equilibrium Line Altitude (ELA) for the Karabatkak glacier. The ELA represents the point at which the annual mass balance of the glacier becomes zero. In this case, the mean ELA for the Karabatkak glacier was calculated to be 4000m.

The simulation run conducted in our research demonstrated that setting the ELA significantly reduced the overestimation of glacier runoff, particularly during periods of high-temperature spikes. However, it is worth noting that calculating the ELA for each individual glacier in the basin posed challenges in terms of model computation. As a result, a mean ELA value for the entire basin was utilized instead. This mean ELA value was derived from the RGI dataset and represents the average ELA value across the basin.

To calculate the mean ELA value for the basin, the following equation was employed, as proposed by K.C. Leonard in 2003:

$$ELA = 46.81 + 0.99 * mean\,altitude$$

To mitigate errors caused by delineation in the glacier dataset, if the glacier area exceeded 1 km^2, the mean altitude of small glaciers was used instead.

Using the established conditions, we estimated glacier runoff for each time step in each grid. The conditions considered were as follows:

If the elevation is less than the ELA and the snow water equivalent (SWE) is less than 5mm and the air temperature (T) is greater than 0, then the glacier runoff (Q_g) was calculated using the formula:

$$Q_g = grid\,ratio \times (0.92 \times (0.4648 \times T + 0.5746) \times 1.16e-04)$$

In this equation, T represents the air temperature, ELA refers to the equilibrium line altitude, and SWE represents the snow water equivalent.

By implementing these conditions and calculations, we were able to estimate glacier runoff for each time step in each grid, taking into account the specific characteristics and conditions of the Karabatkak glacier. This approach allowed us to improve the accuracy of our model and provide more reliable estimations of glacier runoff for the study area.

3.4 Topographic Downscaling of Solar Radiation

Solar radiation plays a vital role in driving energy exchange at the Earth's surface, making it crucial to accurately represent its spatial and temporal distribution for simulating and understanding hydrological processes at local and regional scales. In particular, when it comes to energy balance modeling, it is essential to correct input data, and downscaled radiation data is required (Garen and Marks, 2005).

Downscaling techniques are commonly employed to enhance the spatial resolution of radiation data, as reanalysis datasets, while providing global coverage, often have limited spatial resolution. These methods involve incorporating local topographic features into the dataset by utilizing high-resolution digital elevation models (DEMs) with resolutions ranging from 30 to 100 meters. By considering the local topography, these techniques simulate shadowing effects and other local influences on solar radiation patterns more accurately. By utilizing high-resolution DEMs, downscaling techniques can capture the effects of terrain features such as mountains, valleys, and slopes on solar radiation distribution. These local influences can significantly impact the spatial variability of incoming shortwave irradiance, which is crucial for accurately modeling hydrological processes, especially snowmelt processes (Lehning et al., 2006).

Incorporating local topographic features into the downscaled radiation data allows for more precise predictions of incoming shortwave irradiance at a specific location. This improved spatial representation enables more accurate simulations of snowmelt processes, as the amount of solar radiation received by the snowpack significantly influences its melt rate and overall energy balance. By downsizing the radiation data and considering local topographic effects, researchers can obtain a finer resolution and more realistic representation of solar radiation patterns across a study area. This downscaled radiation data serves as a valuable input for hydrological models, enabling improved simulations and a better understanding of the processes influenced by solar radiation, such as evaporation, transpiration, and snowmelt.

Overall, downscaling techniques that incorporate local topographic features into radiation data through high-resolution DEMs are essential for achieving accurate simulations of hydrological processes. By capturing the spatial variability of solar radiation, these techniques enhance the representation of energy exchange at the Earth's surface, leading to more reliable and insightful hydrological models.

We used a 30 m DEM produced with ALOS satellite data (AW3D, Tadono et al., 2014) to create a detailed topography representation of the study area. The downscaling method was based on the difference between the two conditions for incoming solar radiation. The coefficients (R_c) were derived for each grid at each hour during the year as follows:

$$R_c = \frac{(I_p S + I_d V_f + I_r)\cos\theta}{(I_p + I_d)\cos Z}$$

Shortwave downward radiation has been divided into direct (I_p) and diffuse (I_d) obtained from a method based on the solar zenith angle (Z), the clearness index, and the extraterrestrial radiation (Corripio, 2014). θ is an incidence angle, S is a shadowing effect (0 or 1), V_f is a sky-view factor and I_r is a terrain-reflected irradiance. The numerator part of the equation incorporates solar radiation considering topography and the denominator part represents a flat surface. The coefficient R_c has been determined for every hour of an active sun during the day throughout the year with inactive hours set to 0. Thus, one grid contained 8760 correction values representing 365 days, and in leap years, the last 24 hours were duplicated from the last day of the year. In the preprocessing, R_c values of 30 m grids were upscaled to 1 km using weighted averages to match the model's resolution. We used this method to minimise the losses observed with low-resolution DEMs since the difference in total radiation can be significant (Olson and Rupper, 2019).

Cloudiness plays a crucial role in influencing solar radiation and has a significant impact on various hydrological processes. Assessing cloud transmissivity is challenging, particularly in regions with data scarcity and complex topography, such as high-altitude areas where cloud formation is influenced by the terrain. However, studies conducted on Kara-Batkak Glacier have demonstrated that cloud intensity can be parameterized using precipitation data, providing a valuable approach to estimate cloud transmissivity (Rybak et al., 2021). By utilizing precipitation data as a parameter for cloud intensity, researchers can indirectly infer cloud transmissivity. This approach takes advantage of the relationship between precipitation and cloud formation, allowing for a more comprehensive understanding of cloudiness in areas where direct cloud measurements may be limited.

When defining cloud transmittance coefficients to correspond to clear-sky situations more broadly, there is a notable improvement in ice melt modeling performance. This suggests that incorporating a more accurate representation of cloud transmissivity in hydrological models leads to more reliable simulations and predictions (Pellicciotti et al., 2011). The parameterization of cloud intensity using precipitation data provides a practical solution for estimating cloud transmissivity in data-scarce regions. By leveraging the relationship between precipitation and cloud formation, researchers can indirectly capture the impact of clouds on solar radiation. This approach allows for a more realistic representation of cloudiness in hydrological models, enabling improved simulations of various processes influenced by solar radiation, such as ice melt on glaciers.

Understanding cloud transmissivity is crucial as it directly affects the amount of solar radiation reaching the Earth's surface. By accurately parameterizing cloud intensity and incorporating this information into hydrological models, researchers can better capture the energy balance and associated processes, leading to more reliable predictions of ice melt and other hydrological responses.

In this study, we used a simple approach to correct clear-sky solar radiation using an expression by Greuell et al. (1997) to define cloud transmissivity (τ_{cl}), previously implemented in the modeling of Abramov glacier (Kronenberg et al., 2022):

$$\tau_{cl} = 1.00 - c1 * n - c2 * n^2$$

The total cloud cover (n) data was taken from the ERA5 reanalysis. The coefficients ($c1, c2$) were derived by best-fit regression analysis using solar radiation data from three AWSs (Figure 3.1b) located in high-altitude areas of the study region. Two are located on Bordu and Kara-Batkak glaciers, and one near Batysh-Sook Glacier. The solar radiation coefficients used in the model were separated into two periods to account for seasonal variations in solar intensity: A cold period from October to March, where the coefficients c1 and c2 were set at 0.248 and 0.216 respectively and a warm period from April to September, where the coefficients c1 and c2 were set at -0.06 and 0.289 respectively. Summarising the above methods of topographic downscaling and accounting for the influence of clouds, the following expression was derived:

$$H_{SR} = H_{SRcs} * R_c * \tau_{cl}$$

Where H_{SR} is corrected shortwave downward radiation, H_{SRcs} is a clear-sky shortwave downward radiation from ERA5 database, R_c is derived radiation correction factor and τ_{cl} is calculated as cloud transmissivity.

3.5 Model Performance Evaluation

The evaluation of hydrograph simulation is a critical step in assessing the performance and accuracy of hydrological models. To evaluate the model's performance, several metrics are commonly used, including the Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), and percent bias (PBIAS). The NSE is a widely used metric that compares the simulated values with the observed values to quantify the overall performance of the model (Nash and Sutcliffe, 1970). It measures the agreement between the observed and simulated hydrographs, with values ranging from $-\infty$ to 1. A value close to 1 indicates a good fit between the simulated and observed data, suggesting a high level of accuracy in the model's representation of the hydrological processes.

The KGE is a relatively more recent metric developed by Gupta et al. (2009). It incorporates both the correlation coefficient and the standard deviation ratio of observed and simulated data. The KGE provides a more comprehensive evaluation of the model's performance by considering the correlation, bias, and variability of the simulated hydrograph in relation to the observed data. This metric allows for a more nuanced assessment of the model's accuracy, accounting for both the timing and magnitude of the hydrograph.

The PBIAS (%) metric measures the overall bias of the simulations. It quantifies the average difference between the simulated and observed values, expressed as a percentage of the observed mean value (Moriasi et al., 2015). PBIAS values near zero indicate a good fit between the simulated and observed data, suggesting minimal bias in the model's representation of the hydrological processes.

Each of these evaluation metrics provides valuable insights into the performance of hydrological models. The NSE offers an overall evaluation of the model's performance, allowing for a quick assessment of its accuracy. The KGE and PBIAS, on the other hand, provide a more detailed view of the model's accuracy, considering factors such as correlation, bias, and variability. By using a combination of these metrics, researchers can gain a comprehensive understanding of the model's strengths and weaknesses, enabling them to make informed decisions about model improvements and further research.

Chapter 4: Results and Discussion

4.1 Evaluation of Meteorological Forcing

The results obtained from the comparison of observed data on Kara-Batkak glacier reveal the significant influence of clouds, particularly during the summertime. On cloudy days, the maximum values of daytime radiation in the warm period are reduced, and the total values are dependent on the characteristics of the topography. This indicates that clouds play a crucial role in shaping the radiation patterns on the glacier.

In order to further understand the impact of clouds, we compared the values obtained from the ERA5 default data. The ERA5 data already accounts for the influence of clouds to some extent (Hersbach et al., 2020). On Kara-Batkak glacier, the default values showed a mean absolute error (MAE) of 79.63 (W m-^{2}) and a Pearson correlation coefficient of 0.88. However, when using the corrected data that considered the influence of clouds more accurately, the MAE reduced to 38.15 (W m-^{2}), and the Pearson correlation coefficient decreased slightly to 0.85. This suggests that the corrected data provides a more precise estimation of the radiation values, taking into account the specific cloud characteristics of the region.

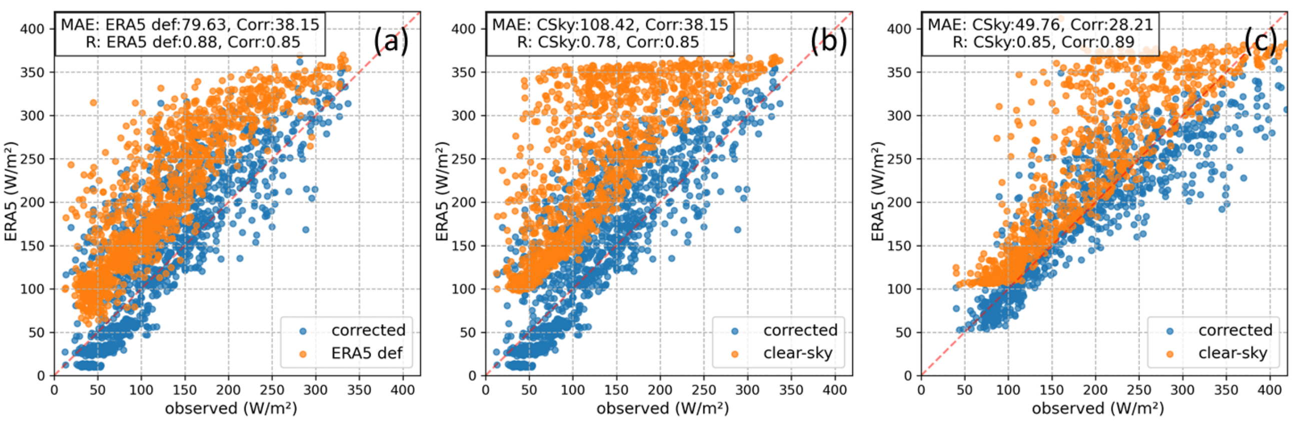

Figure 4.1: Correction of shortwave radiation. a) Data from AWS on Kara-Batkak glacier with default ERA5 b) Kara-Batkak with clear-sky c) Bordu with clear-sky.

It is important to note that the location of the weather station plays a role in these observations. The AWS (Automatic Weather Station) on the ablation tongue of Kara-Batkak glacier is surrounded by steep slopes, while the station on the Bordu glacier is situated on a flatter and more open slope. This difference in location and topography is reflected in the data, as seen in Figure 4.1c. The lower values observed in the cold period at the Bordu glacier station exhibit a slight deviation compared to the Kara-Batkak site. This discrepancy can be attributed to the variations in topography and the associated microclimate conditions at each station.

In summary, the comparison of observed data on Kara-Batkak glacier highlights the significant influence of clouds, particularly during the summertime. The corrected data, which considers the cloud influence more accurately, shows improved performance in terms of MAE and Pearson correlation coefficient compared to the default data. Additionally, the differences observed between the AWS locations on Kara-Batkak and Bordu glaciers can be attributed to variations in topography and microclimate conditions. These findings emphasize the importance of considering cloud characteristics and topographical factors when analyzing radiation patterns on glaciers.

4.2 Evaluation of Model Simulations

The Chon-Kyzyl-Suu river basin, depicted in Figure 3.1a, is characterized by its extensive glaciated area and experiences its peak flow during the months of July and August. This information was validated through the simulation results, which provided evaluation metrics such as the Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), and percent bias (PBIAS). The NSE, KGE, and PBIAS values obtained were 0.785, 0.75, and 9.67%, respectively.

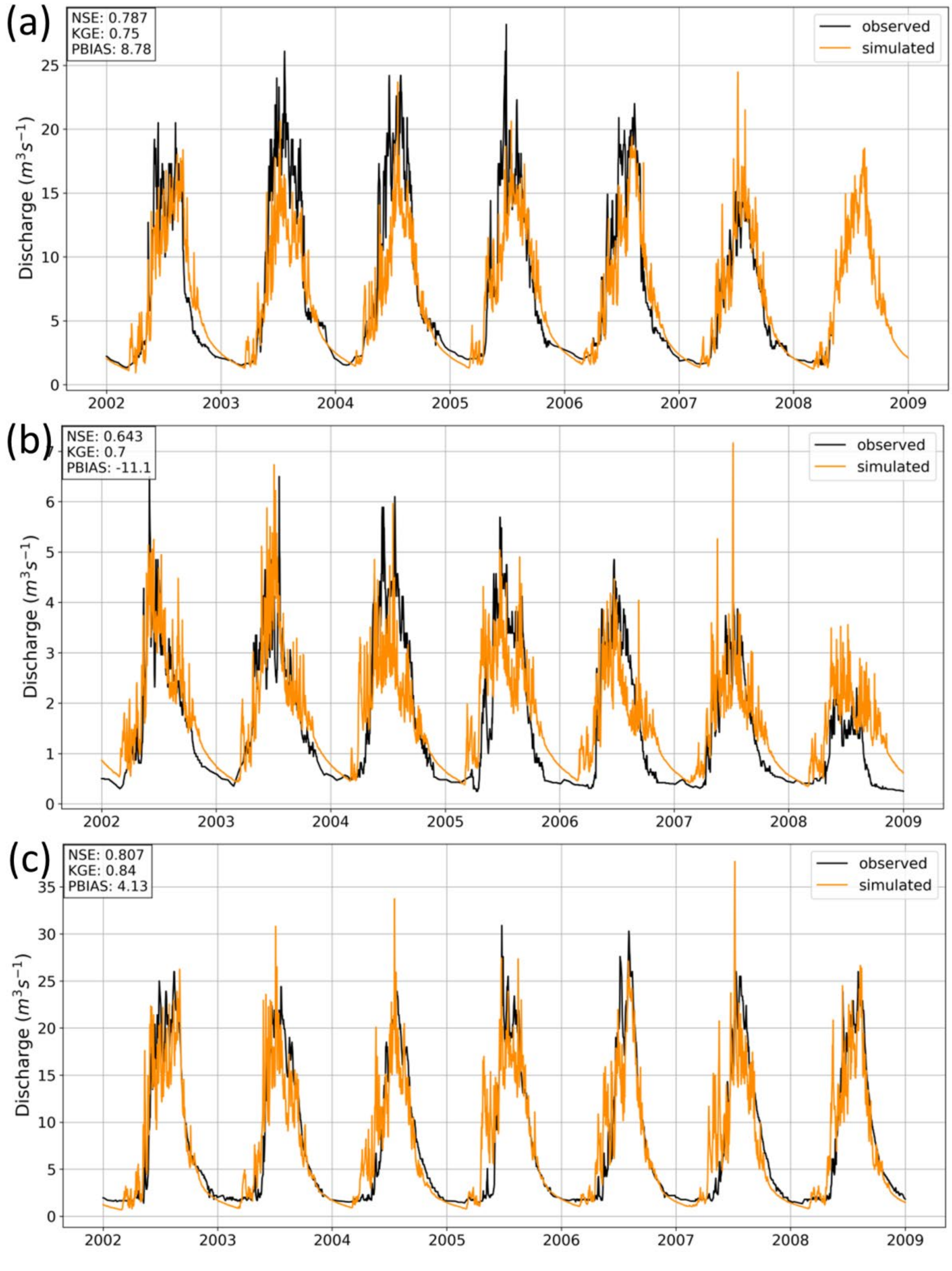

Figure 4.2: Discharge between 2002 and 2009 of a) Chon-Kyzyl-Suu, b) Kichi-Kyzyl-Suu, and c) Djuuku basins.

These metrics indicate that the model's simulations performed reasonably well in capturing the overall behavior of the hydrological processes in the Chon-Kyzyl-Suu river basin. The NSE value of 0.785 suggests a relatively good agreement between the observed and simulated values, indicating a satisfactory overall performance of the model. Similarly, the KGE value of 0.75 indicates a reasonable correlation and variability match between the observed and simulated data.

However, it is important to note that the PBIAS value of 9.67% indicates a slight bias in the simulated values. This suggests that the model may have a tendency to overestimate or underestimate the observed runoff, resulting in a slight deviation from an ideal fit. Further investigation into the sources of this bias could help refine the model and improve its accuracy.

Unfortunately, a significant setback occurred during data collection as part of the 2008 runoff gauge malfunctioned, resulting in the loss of data for that period. This data gap poses a challenge in fully assessing the model's performance during that specific time frame. However, it is important to acknowledge and account for this limitation when interpreting the overall results and drawing conclusions.

The Kichi-Kyzyl-Suu small basin, represented in Figure 4.2b, has received relatively less attention in terms of research, and the availability of meteorological data is limited, making it challenging to assess its climatic characteristics. However, despite these limitations, hydrograph simulations were conducted in order to gain insights into the basin's hydrological behavior. The simulation results yielded evaluation metrics including the Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), and percent bias (PBIAS) values.

The NSE value of 0.643 indicates a moderate agreement between the observed and simulated hydrographs. This suggests that the model reasonably captures the overall variability and timing of the observed hydrological processes in the Kichi-Kyzyl-Suu small basin. Similarly, the KGE value of 0.72 suggests a reasonable correlation and variability match between the observed and simulated hydrographs. This further indicates that the model is capable of capturing the key characteristics of the hydrological processes in the basin, considering the limited availability of meteorological data. However, it is important to note the negative PBIAS value of -9.49%. This implies a slight underestimation of the observed runoff by the model, indicating a tendency to predict lower values compared to the actual measurements. This bias needs to be carefully considered when interpreting the results and drawing conclusions from the simulations.

Due to the lack of meteorological data for the Kichi-Kyzyl-Suu small basin, it becomes more challenging to comprehensively assess its climatic features. This data gap limits our ability to understand the influence of meteorological variables on the basin's hydrological processes and further investigate the drivers of the observed hydrograph behavior.

To overcome this limitation, future research efforts should focus on collecting meteorological data within the basin, allowing for a more comprehensive analysis of the climatic characteristics and their impact on the hydrology. Integration of remote sensing data and the use of hydrological models that can leverage limited meteorological data could also provide valuable insights into the basin's hydrological behavior.

The Djuuku River basin, depicted in Figure 4.2c, is the largest among the studied basins. However, its position in the western region results in less influence from Lake Issyk-Kul on precipitation patterns. Unfortunately, meteorological data for this basin is not available, which poses a challenge in assessing its climatic characteristics. Nevertheless, hydrograph simulations were conducted to gain insights into the basin's hydrological behavior. The evaluation metrics, including the Nash-Sutcliffe efficiency (NSE), Kling-Gupta efficiency (KGE), and percent bias (PBIAS), were used to assess the performance of the simulations.

The NSE value of 0.806 suggests a good agreement between the observed and simulated hydrographs in the Djuuku River basin. This indicates that the hydrological model captures the overall variability and timing of the observed hydrological processes reasonably well. Similarly, the KGE value of 0.84 indicates a strong correlation and variability match between the observed and simulated hydrographs. This suggests that the model effectively captures the key characteristics of the basin's hydrological processes, considering the absence of meteorological data. The PBIAS value of 4.57% indicates a slight bias in the model's prediction of the observed runoff. This suggests a tendency to slightly overestimate the observed streamflow, although the bias is relatively small.

The similarity of these evaluation metrics to those obtained for the Chon-Kyzyl-Suu basin indicates that the model is able to capture the influence of glaciers on the water balance and streamflow dynamics in both basins. This suggests that the model adequately represents the hydrological processes associated with the glaciers in these regions. Given the limited availability of meteorological data, it is important to interpret these results with caution. While the simulations show promising performance, the absence of meteorological data limits our understanding of the climatic drivers of hydrological processes in the Djuuku River basin.

The three study basins, namely the Issyk-Kul Lake basin, Kichi-Kyzyl-Suu basin, and Chon-Kyzyl-Suu and Juuku basins, exhibit varying degrees of glaciation and distinct precipitation patterns. These factors contribute to differences in the hydrological behavior and seasonal runoff patterns observed in each basin. The Issyk-Kul Lake basin is characterized by a precipitation gradient, primarily influenced by moisture transfer from the lake. This moisture transfer occurs predominantly from west to east, resulting in varying precipitation levels across the basin. This spatial variation in precipitation directly impacts the seasonal patterns of runoff within the basin.

In the Kichi-Kyzyl-Suu basin, the maximum runoff occurs in May-June. This timing indicates that the basin experiences a peak flow during the early summer months. The primary driver of runoff in this basin is likely related to factors other than glacial melt, as the basin exhibits relatively less glaciation. Other factors such as snowmelt and rainfall patterns are likely to play a more significant role in driving the hydrological processes. On the other hand, the Chon-Kyzyl-Suu and Juuku basins demonstrate peak runoff values in July-August. This timing suggests that these basins experience their highest flow rates during the peak summer months. The primary driver of runoff in these basins is likely attributed to glacial melt due to their extensive glaciated areas. The melting of glaciers during the summer months contributes significantly to the overall water balance and streamflow dynamics in these basins.

The contrasting runoff patterns among the study basins highlight the importance of considering the influence of glaciation and precipitation patterns on the hydrological behavior of each basin. The presence or absence of glaciers, along with the spatial variation of precipitation, significantly shapes the seasonal patterns of runoff and overall water availability in these basins. Understanding these variations is crucial for effective water resource management and planning in the region. It allows for the identification of critical periods of high and low flow, which can aid in optimizing water allocation, hydropower generation, and mitigating the impacts of potential water scarcity during certain times of the year.

In summary, the study basins exhibit different ratios of glaciation and distinct precipitation patterns that influence their hydrological behavior. The Issyk-Kul Lake basin demonstrates a precipitation gradient due to moisture transfer from the lake, impacting the seasonal runoff patterns. The Kichi-Kyzyl-Suu basin experiences maximum runoff in May-June, while the Chon-Kyzyl-Suu and Juuku basins exhibit peak values in July-August, primarily due to the influence of glacial runoff. These variations highlight the significance of considering the role of glaciation and precipitation in understanding the hydrological dynamics of each basin.

Figure 4.4 presents comparative data from a gauging station near Karabatkak glacier, which is located in a region that is not easily accessible throughout all seasons except summer. Due to this limitation, we utilized the available summer data to compare with the results of our river flow modeling. The purpose of this comparison was to assess the model's ability to accurately reproduce runoff, even in small river basins like the one near Karabatkak glacier. We wanted to evaluate whether the model could capture the relative fluctuations in runoff caused by various factors, such as sudden temperature increases and precipitation events.

The results of our analysis showed promising outcomes. The model demonstrated a comparative ability to reproduce the observed runoff patterns, indicating its reliability in simulating river flow dynamics. Despite the challenges associated with limited data availability in this particular location, the model was able to capture the general trends and fluctuations in runoff.

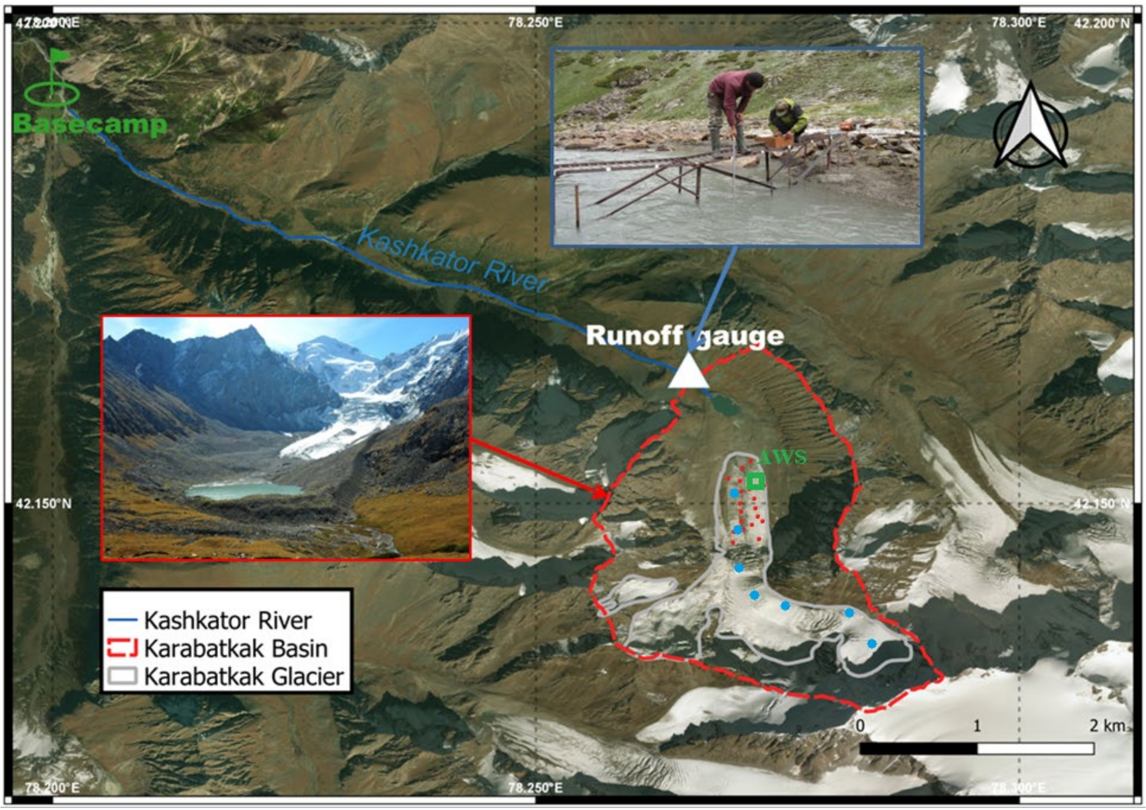

Figure 4.3: Kara-Batkak glacier and Kashkator river area. Location of ablation stakes on the lower part of the glacier (red dots), snow pits (blue dots) and AWS (greed rectangle).

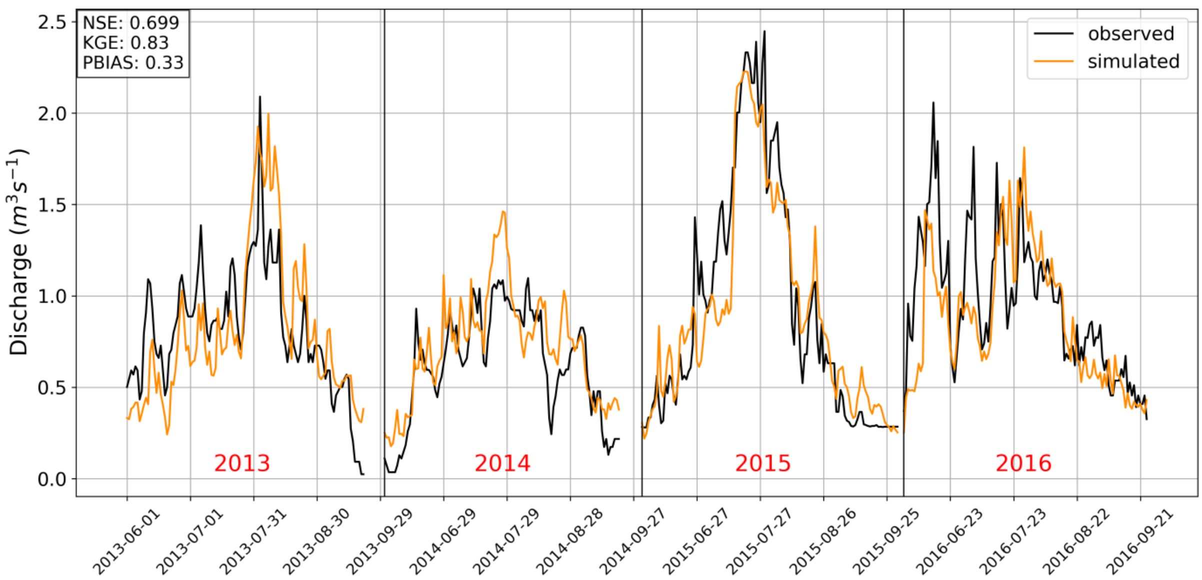

Figure 4.4: Modeled summer discharge of Kashkator River at headwaters (Figure 4.3) compared with runoff gauge.

4.3 Impact of Topographic Downscaling on Ice and Snow Melt Processes

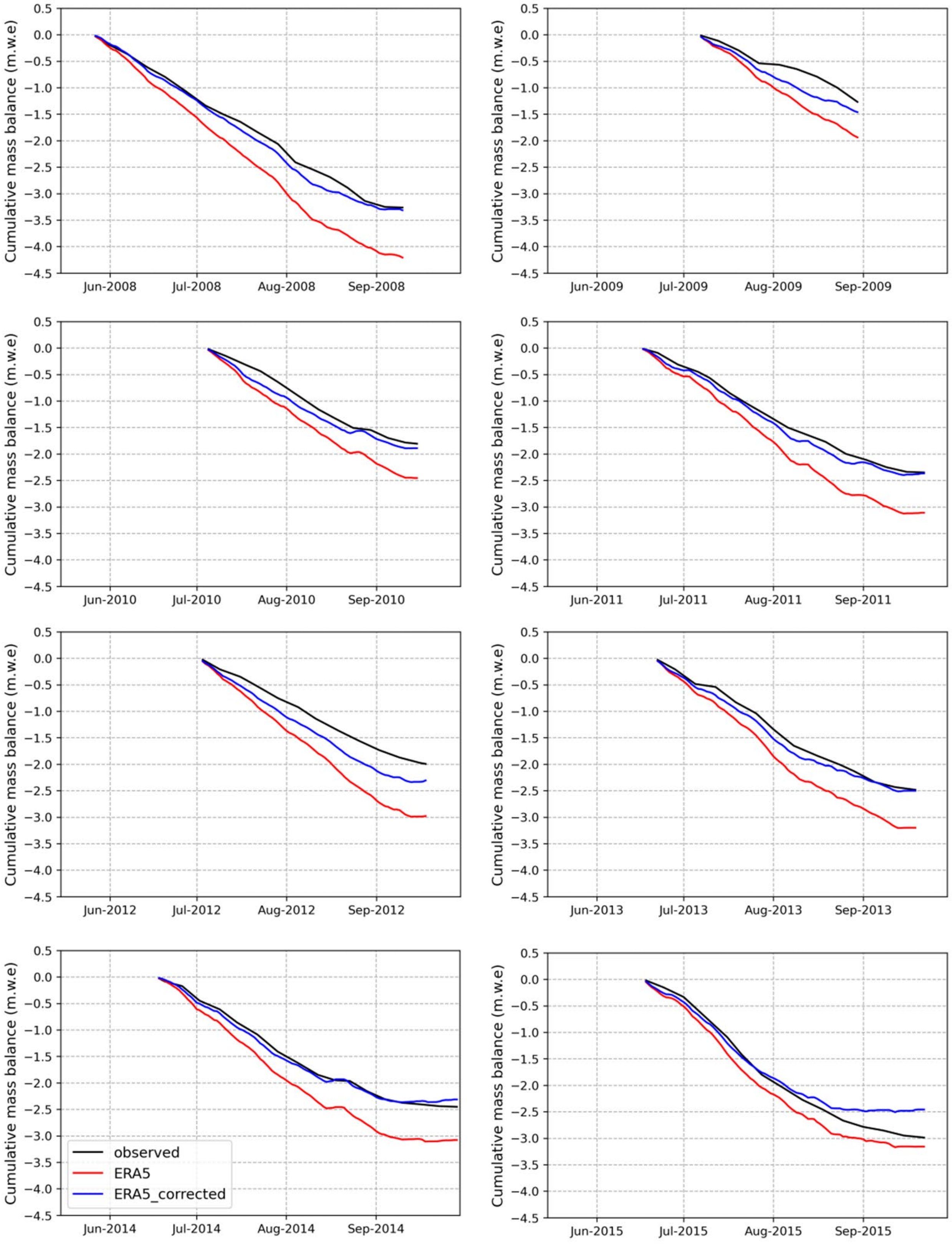

Figure 4.5: Comparison of observed and simulated mass balances with and without

shortwave downward radiation correction on the lower part of Kara-Batkak glacier. Observed values are aggregated stake measurements on ablation zone (Figure 4.3).

The Kara-Batkak glacier tongue, as depicted in Figure 4.3, is surrounded by mountain slopes that result in prolonged shading throughout the day. To monitor the melting of the lower part of the glacier, the Tien-Shan High Mountain Scientific Center of the Academy of Sciences of Kyrgyzstan has deployed twenty-one stakes within the glacier's ablation zone. These stakes provide valuable data on the rate of ablation, or melting, of the glacier. A comparative analysis was conducted between the observed ablation data and the modeling results for the period from 2008 to 2015. It was found that there was a notable difference in the melting rate, which was primarily attributed to the input data used in the models.

The modeling results utilizing corrected meteorological forcing data from ERA5, which incorporates topographic and cloud-based adjustments for shortwave downward radiation, showed a higher level of accuracy compared to the observations. The Root Mean Square Error (RMSE) for these simulations was 0.23 meters water equivalent (m w.e.), and the Mean Absolute Error (MAE) was 0.17 m w.e. These values indicate a relatively small margin of error between the modeled and observed ablation rates.

On the other hand, when uncorrected ERA5 data was utilized in the modeling process, the results showed a larger deviation from the observed ablation rates. The RMSE for these simulations was 0.73 m w.e., and the MAE was 0.69 m w.e. These values indicate a higher level of error in the modeling results compared to the corrected data.

The utilization of uncorrected ERA5 data without incorporating adjustments for topography resulted in an overestimation of the melting rates within the Kara-Batkak glacier tongue. On average, the simulations based on uncorrected data overestimated the melting rates by approximately 30%.

The findings from this analysis underscore the importance of using accurate and corrected meteorological data in glacier mass-balance simulations. The inclusion of topographic and cloud-based adjustments for shortwave downward radiation in the ERA5 data significantly improved the accuracy of the modeling results. This highlights the need for careful consideration of the input data and the incorporation of relevant adjustments to ensure reliable and precise simulations.

4.4 Comparison with Measurements on Bordu Glacier

The results obtained from the mass balance of the GLIMB model were compared with the observed data on the Bordu glacier, as shown in Figure 4.6. To measure the snow water equivalent (SWE), a SnowFox device, which is a cosmic ray neutron sensor produced by

Hydroinnova, was used (as seen in Figure 3.1d). Additionally, the melting of the glacier surface was measured using a Sonic Ranger (Campbell SR50A), taking into account an ice density of 900 kg m-³.

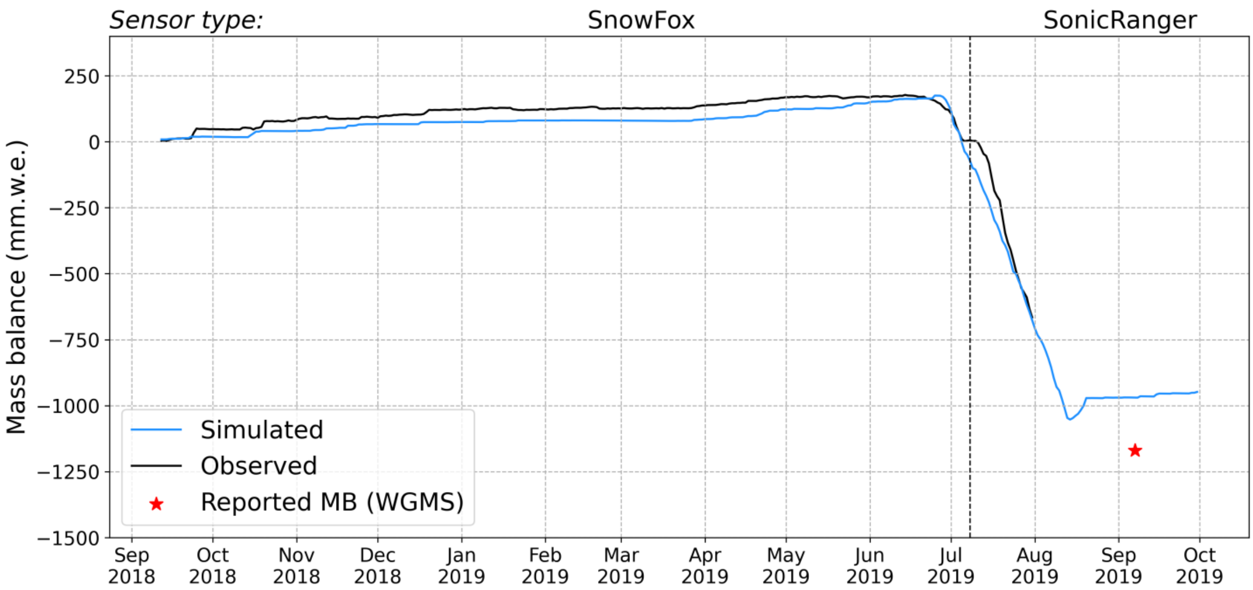

Figure 4.6: Observed and simulated daily mass balance at Bordu glacier (4137 m a.s.l.). Red star indicates seasonal mass balance change at the end of the observation period (2018/09/12-2019/09/07) reported to World Glacier Monitoring Service (WGMS)(Zemp et al., 2021). Sensor type indicates a recording instrument for a certain period of observations.

In the 2019 modeling, the maximum seasonal snow accumulation was recorded on June 25th, with a value of 175 mm water equivalent (w.e.). The data measured with cosmic rays using the SnowFox device showed a slightly different maximum on June 14th, with a value of 177 mm w.e. It is worth noting that the GLIMB model did not consider snow transport by wind, which was recorded by the SnowFox device.

Due to technical issues, the Sonic Ranger couldn't record ice melting in August 2019, and therefore, the data reported by the World Monitoring Service (WGMS) from observations was used instead. At an elevation of 4100-4200 m above sea level (the Automatic Weather Station is located at 4137 m a.s.l.) on the Bordu Glacier, the seasonal mass balance for 2019 was calculated as -1170 mm w.e. In comparison, the maximum modeled seasonal melt during the same period was -1053 mm w.e.

The difference between the observed and modeled results can be attributed to the influence of precipitation. Precipitation plays a significant role in ice melt results. In cases where snowfall occurs during the observation period, which is a common event on the glacier during summer, ice melting is interrupted until the snowpack melts completely

(Fujita and Ageta, 2000).

These findings highlight the importance of considering not only the direct measurements but also the influence of external factors such as wind-induced snow transport and precipitation when modeling glacier mass balance. Although the GLIMB model provided valuable insights, the discrepancies between the observed and modeled results emphasize the need for continuous monitoring and refinement of the model to improve its accuracy and reliability.

4.5 Runoff Components in Glaciated Basins

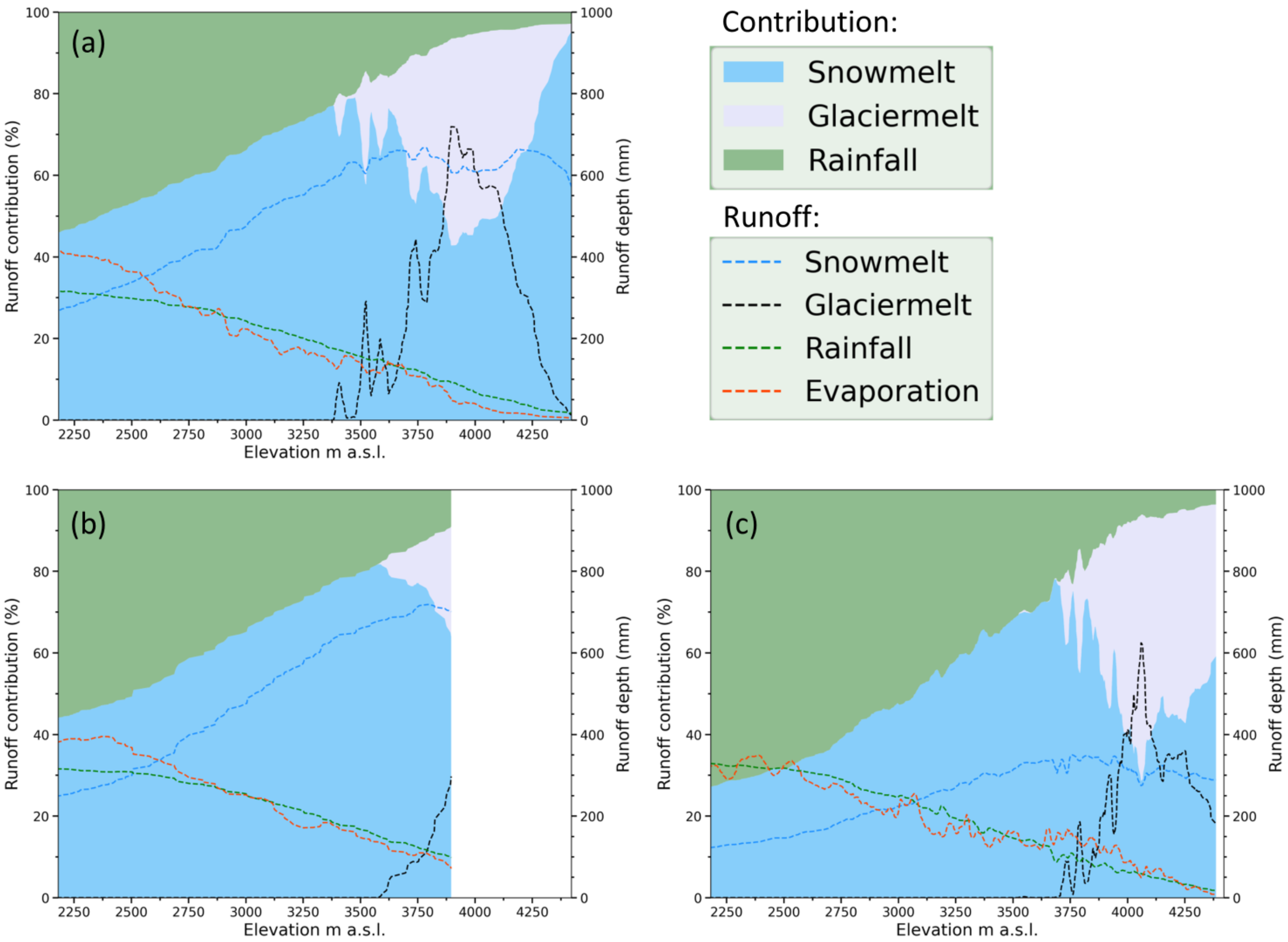

Figure 4.7: Runoff components along elevation for a) Chon-Kyzyl-Suu, b) Kichi-Kyzyl-Suu, and c) Djuuku. The left axis represents the percentage of the total runoff. The right axis represents runoff depth. Evaporation is given in absolute values.

The analysis of the components of river basin runoff was conducted using modeling results, which were then compared with average elevation values. Figure 4.7 provides a visual representation of the relationship between elevation, the percentage of each component, and the runoff of components in millimeters. It reveals that as altitude increases, the contribution of rain to the basin runoff decreases, while the contribution of snow increases. This indicates that at higher elevations, precipitation is more likely to fall as snow rather than rain.

Furthermore, as we move from the beginning of the glacier zone, the contribution of ice melting to the basin runoff becomes more significant. This suggests that the melting of ice within the glacier zone has a substantial impact on the overall runoff in the basin. In contrast, evaporation decreases with elevation. For instance, in the Chon-Kyzyl-Suu basin within the 2100-2200 m a.s.l. zone, evaporation was estimated to be 400 mm. However, at 4400 m a.s.l., the value was close to zero. This reduction in evaporation is attributed to lower temperatures and reduced availability of water vapor in the atmosphere at higher elevations.

The contribution of glaciers to runoff in different basins is influenced by the extent of glaciation and precipitation patterns. In the Chon-Kyzyl-Suu Basin, which has a glaciated area covering approximately 11.4% of the total area, glaciers contribute around 50% of the water runoff during the months of July and August, and 23% annually. Snowmelt and rainfall, on the other hand, contribute 60% and 17% respectively to the total runoff in this basin (as shown in Figure 4.7).

In the Kichi-Kyzyl-Suu Basin, which has a lower extent of glaciation at only 1.8% of the area, the primary contributors to runoff throughout the year are snowmelt and rainfall, accounting for 64% and 22% respectively. Glaciers play a smaller role in this basin, contributing around 25% of the water runoff during July and August, and 8% annually.

Similarly, in the Djuuku Basin with a glaciated area of 8.3%, glaciers contribute approximately 54% of the water runoff during July and August, and 27% annually. Snowmelt and rainfall make up 50% and 23% of the total runoff, respectively. It is important to note that the contribution of glaciers to seasonal runoff not only depends on the degree of glaciation but also on the amount and distribution pattern of precipitation. Different basins exhibit varying degrees of glaciation and precipitation, resulting in differing contributions of glaciers, snowmelt, and rainfall to the overall runoff.

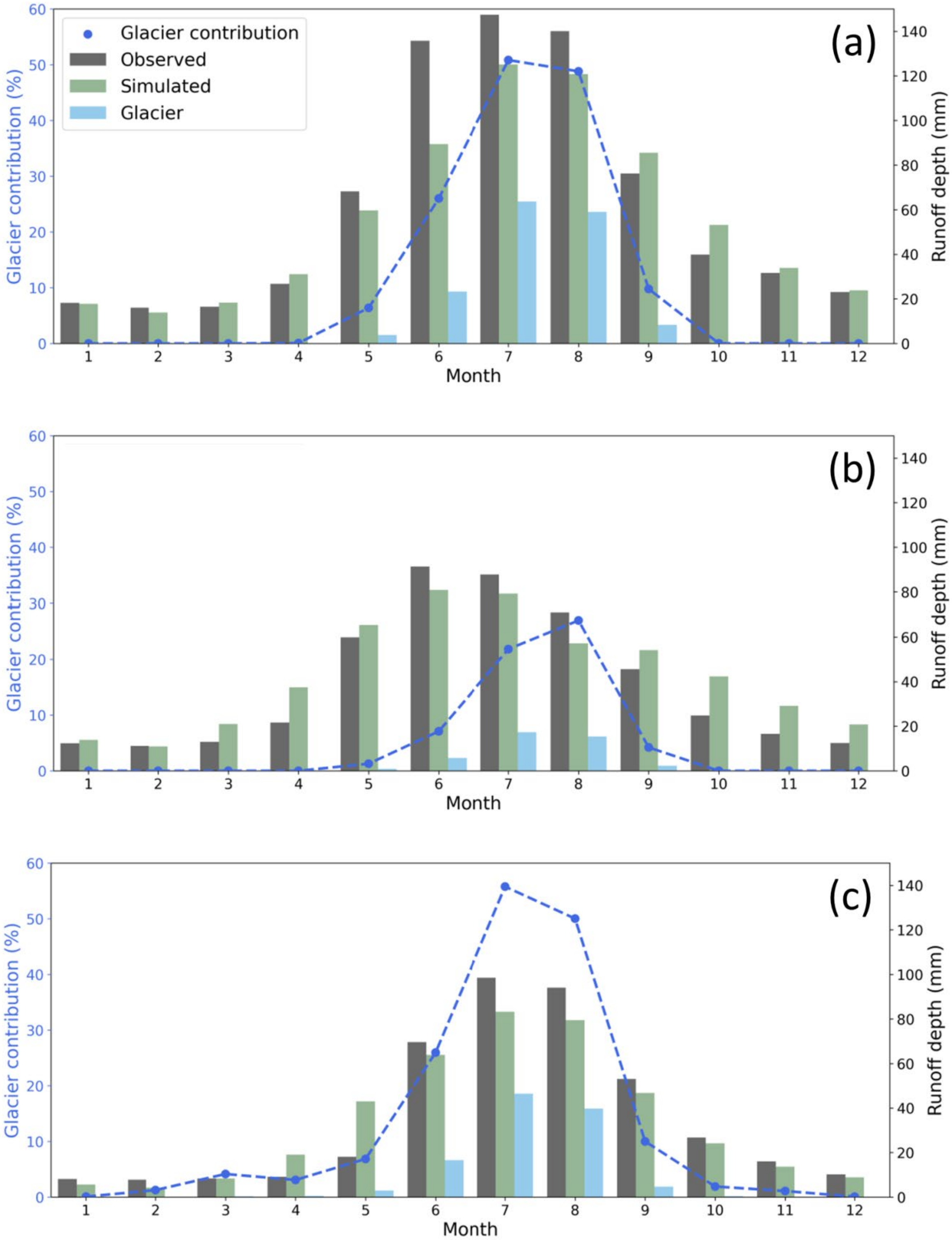

Figure 4.8: Monthly runoff depths and glacier contribution for a) Chon-Kyzyl-Suu b) Kichi-Kyzyl-Suu c) Djuuku basins (2002-2008).

4.6 Insights into Hydrological Dynamics and Factors Influencing Runoff

Glacier melt-induced droughts pose a significant concern in the context of changing hydrological patterns. The impact of glacier runoff on water availability during dry years is an important topic in hydrological research. Numerous studies have highlighted the crucial role of glacier melt in buffering water availability during periods of low precipitation. Researchers have emphasized the contribution of glacier storage change to runoff, particularly in large-scale drainage basins in Europe (Huss, 2011). This underscores the importance of considering glacier runoff in hydrological assessments. Glacier melt serves as an additional water source, compensating for errors in runoff models in glacierized catchments and influencing basin precipitation estimates.

Studies have also shown the potential of increasing glacial meltwater to alleviate the severity and duration of droughts in rivers that heavily rely on glacier melt as their primary recharge source, especially in arid regions (Chen et al., 2019). Glacier meltwater has been found to make a non-negligible contribution to river runoff, particularly during drought years, further highlighting the significance of glacier runoff in sustaining water availability during dry periods. The fluctuations in summer glacier melt peaks have been identified as a driver of streamflow drought. This dynamic nature of glacier runoff plays a crucial role in water availability. Considering glacier melt as a crucial component in hydrological models and water resource management strategies is essential, particularly in glacierized catchments.

Analyzing the glaciological runoff on the total river runoff in the Chon-Kyzyl-Suu, Juuku, and Kichi-Kyzyl-Suu basins has revealed valuable insights about the relationship between precipitation, glacial runoff, and river flow. We calculated the Standardized Precipitation Index (SPI) in each basin from 2003 to 2019, considering both precipitation and glacial runoff data (Figure 4.9-4.11).

The findings indicate that river runoff is influenced not only by the precipitation regime and its pattern but also by the glaciological component of the river. By comparing the SPI values for precipitation alone and considering the contribution of glacial runoff, we were able to identify a clear relationship between annual precipitation and glacial runoff.

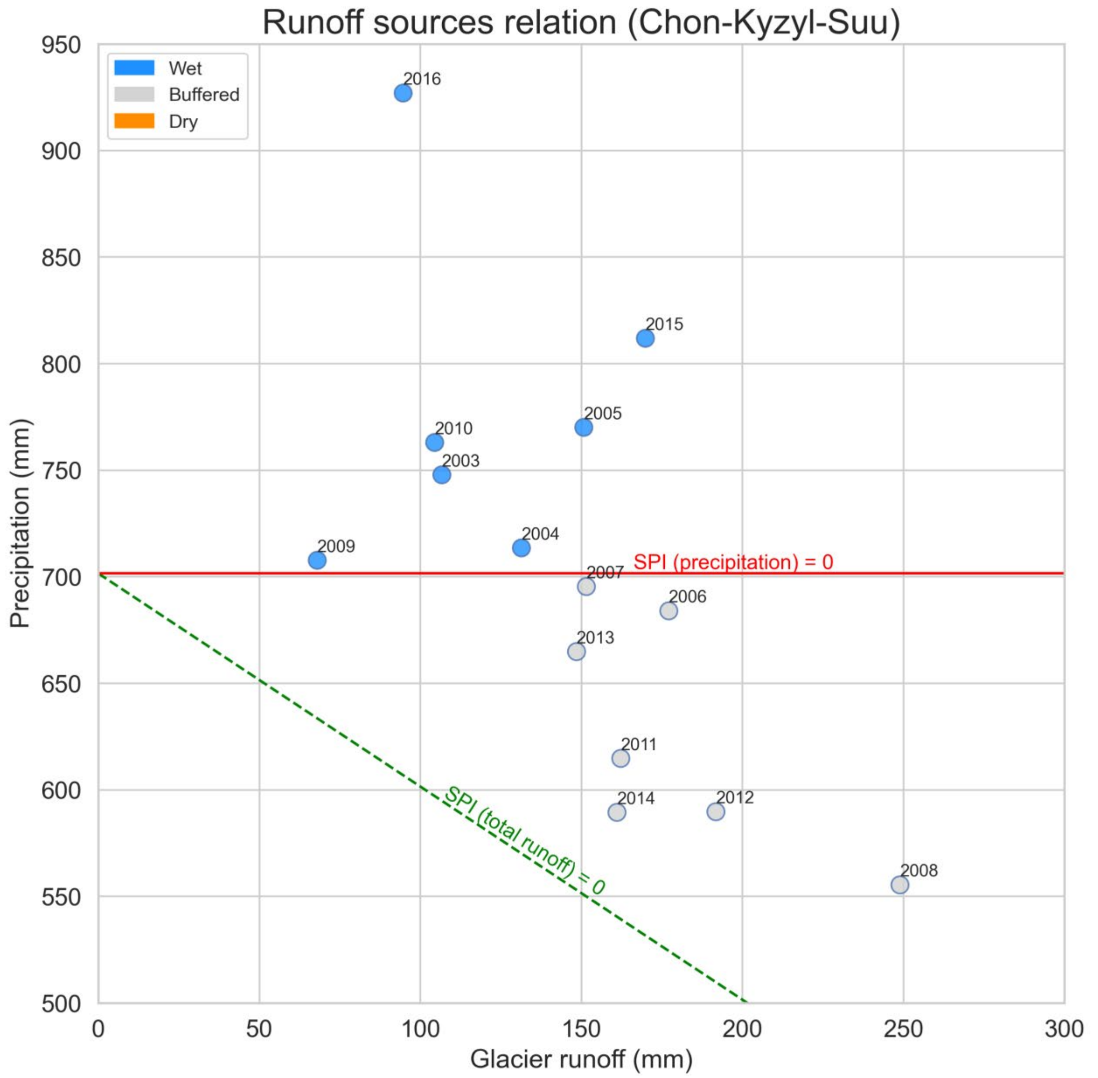

Figure 4.9 Glacier runoff and precipitation relationship. Red line represents SPI index = 0, green dashed line represents SPI index considering total runoff for Chon-Kyzyl-Suu River Basin.

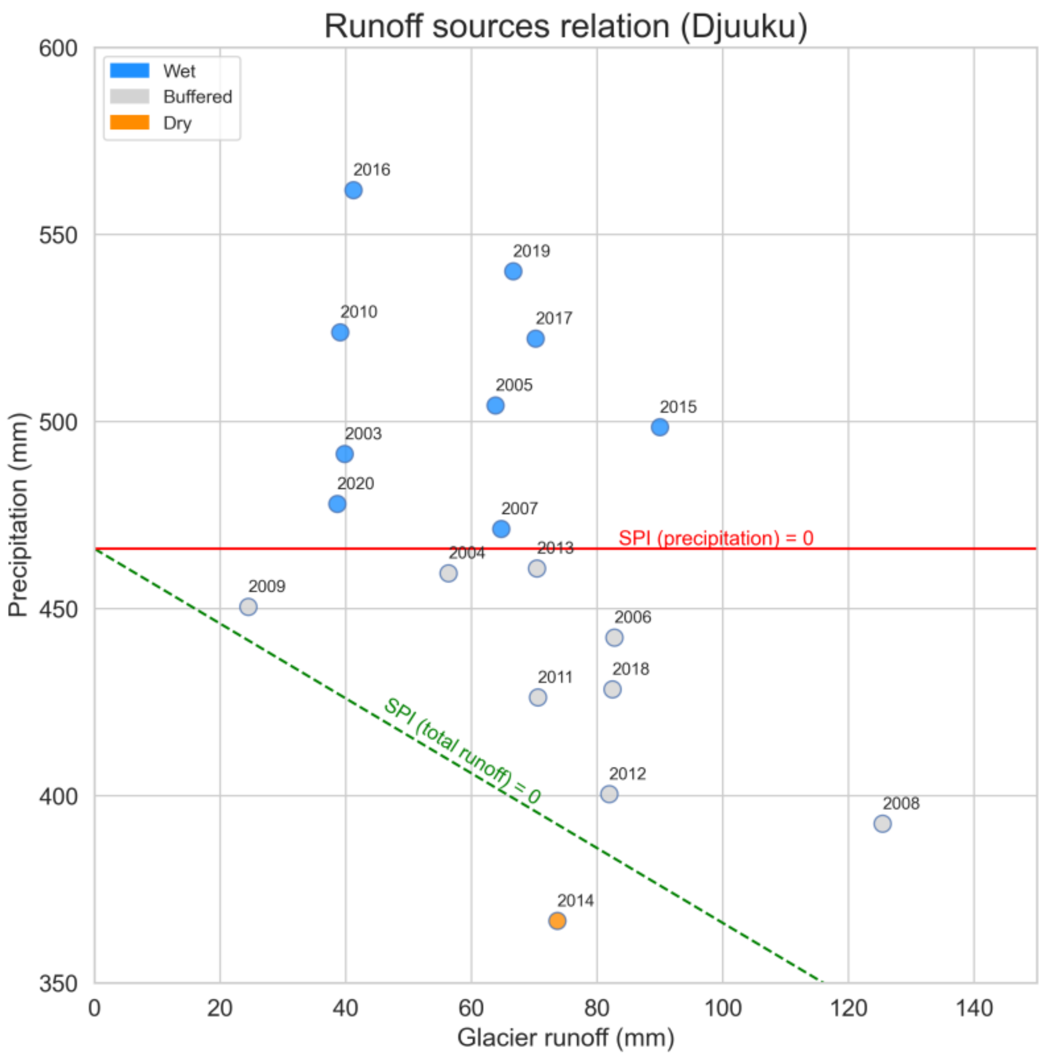

Figure 4.10 Glacier runoff and precipitation relationship. Red line represents SPI index = 0, green dashed line represents SPI index considering total runoff for Djuuku River Basin.

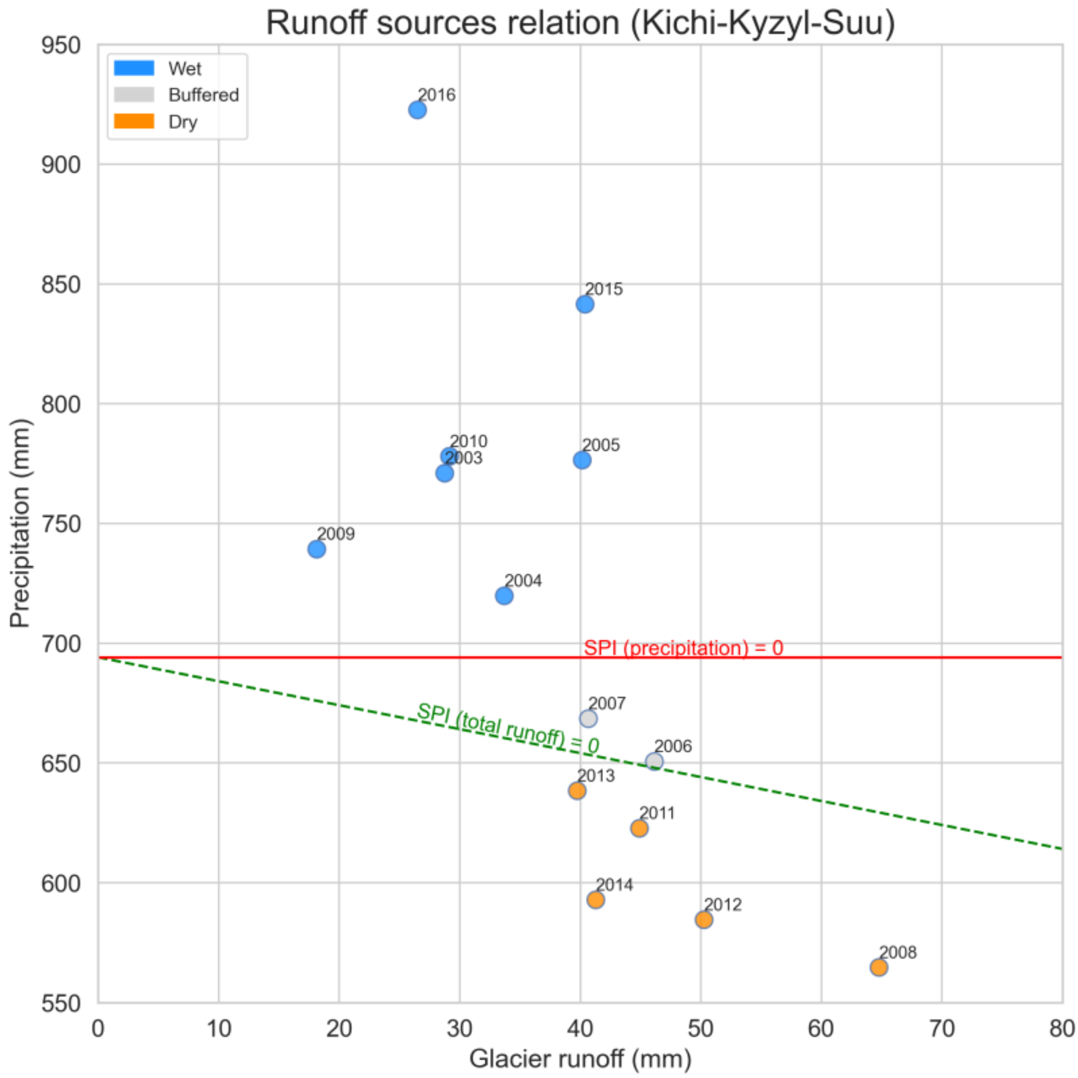

Figure 4.11 Glacier runoff and precipitation relationship. Red line represents SPI index = 0, green dashed line represents SPI index considering total runoff for Kichi-Kyzyl-Suu River Basin.

It is worth noting that the less glaciated Kichi-Kyzyl-Suu River exhibits a decreasing trend in this value due to insufficient glacial runoff supply. The zone between the SPI for precipitation and the SPI for total runoff is minimal in this basin compared to the others studied. This information is crucial in determining the relationship between precipitation and glacial runoff, as well as understanding the influence of glacier area and the buffering effect of glacier runoff in specific years and basins.

These findings provide a broader perspective for each basin when implementing water management plans. As climate change continues to impact glaciers, causing them to melt and shrink in size, their buffer function will gradually diminish. Basins with more glaciers and less precipitation will be particularly affected by these changes. Therefore, understanding the relationship between precipitation and glacial runoff is essential for effective water resource management in the future.

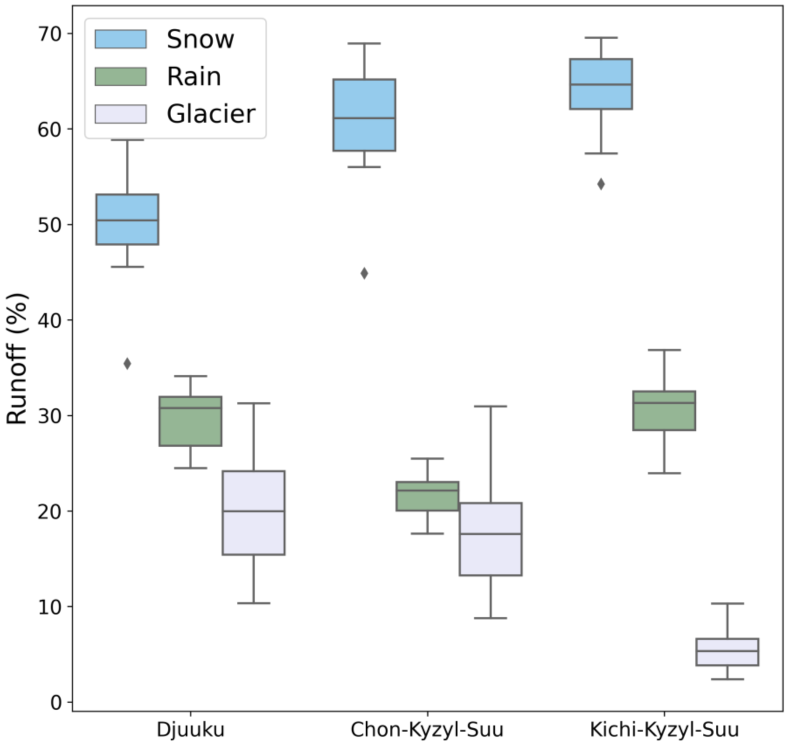

Figure 4.12 Boxplots of runoff sources in study basins.

Figure 4.12 displays boxplots representing the different sources of runoff, namely snow, rain, and glaciers, for each river basin. At the bottom of the figure, we can observe the corresponding river basins: Djuuku, Chon-Kyzyl-Suu, and Kichi-Kyzyl-Suu.

The boxplots provide valuable information about the variations in the glacial component of runoff in each basin. In particular, the Djuuku and Chon-Kyzyl-Suu basins exhibit significant variations, indicating a substantial contribution from glacial sources due to the presence of extensive glaciation in these areas. On the other hand, the Kichi-Kyzyl-Suu basin shows relatively smaller variations, implying a lesser reliance on glacial runoff due to the limited glaciated area.

Interestingly, despite the variations in the extent of glaciation in each basin, the glacial component can range from a minimum value of approximately 10% to a maximum value of 10% across all basins. This suggests that even in basins with substantial glaciation, the glacial component may not always be the dominant source of runoff. Similarly, in basins with smaller glaciated areas, the glacial component can still contribute significantly to the overall runoff. Factors such as precipitation patterns, temperature, and the size of the glaciated area all play a role in determining the contribution of glacial runoff. Additionally, the buffering effect of glaciers, which can store water and release it gradually, also influences the glacial component of runoff.

4.7 Climate Change Impact on Naryn River Basin

The Naryn River Basin, located in Central Asia, is known for its extensive snow cover during the winter months. However, with climate change and rising temperatures, the region is likely to experience significant changes in its snow dynamics, which can have profound implications on the hydrological cycle. One of the primary consequences of increasing temperatures is the reduction in snow accumulation and duration of snow cover. As temperatures rise, more precipitation falls as rain instead of snow, leading to a decrease in the overall snowpack. This reduction in snow mass can have far-reaching consequences for water availability, particularly during the dry season when snowmelt serves as a crucial water source.

Regional climate models (RCMs) are valuable tools for studying and projecting future climate conditions at a regional scale. In the case of the Naryn River Basin, where high altitude precipitation plays a crucial role in the hydrological cycle, RCMs can provide more detailed and localized information about precipitation patterns.

In our study, we utilized a high-resolution 5km Nonhydrostatic Regional Climate Model (NHRCM) considering Shared Socioeconomic Pathway (SSP) 585 provided by the Meteorological Research Institute, Japan Meteorological Agency, specifically designed for Central Asia. This dataset is unique and valuable as it offers a more accurate resolution for high mountain areas, considering the crucial aspect of orographic precipitation.

SSP is a scenario developed by the Intergovernmental Panel on Climate Change (IPCC) as part of their Representative Concentration Pathways (RCPs). SSP 585 represents a future trajectory where there is high fossil fuel use and limited climate change mitigation efforts. It is characterized by rapid economic growth, high energy demand, and a heavy reliance on fossil fuel-based energy sources. In this scenario, greenhouse gas emissions continue to increase, leading to a high level of global warming and significant environmental impacts. SSP 585 serves as a reference point for studying the potential consequences of a future with limited climate change mitigation measures.

Regional simulations of glaciated areas often face challenges due to the lack of data or its inaccuracy. Glaciers, being highly sensitive to the accumulation process, require precise inputs to capture their behavior accurately. The quality of precipitation input is particularly critical as it can significantly influence the representation of glacier conditions in simulations. The utilization of the NHRCM dataset addresses this issue by providing a more reliable and detailed representation of precipitation patterns in high mountain areas. This high-resolution model accounts for the complex topographic features and orographic effects that influence precipitation distribution. By capturing these intricate details, the NHRCM can provide a more realistic simulation of precipitation in glaciated regions.

Considering the future projections, the accuracy of precipitation inputs becomes even more important. Changes in precipitation patterns, along with other meteorological forcings, can have a substantial impact on the overall energy and water balance of glaciated systems. Therefore, using a dataset like the NHRCM can help to better understand and predict the potential impacts of climate change on glaciers in Central Asia. By incorporating the NHRCM dataset into our simulation, we can improve the accuracy of our results and enhance our understanding of the response of glaciated systems to changing climate conditions. This, in turn, enables us to assess the potential consequences for water resources, ecosystems, and communities that rely on these glaciated regions for various purposes.

It is worth noting that the availability of such a unique dataset like the NHRCM is a valuable contribution to the scientific community. The ability to access high-resolution climate models specific to Central Asia allows for more targeted research and informed decision-making in the region.

However, it is essential to acknowledge that despite the advancements in regional climate modeling, challenges and uncertainties still exist. Factors such as parameterizations, model physics, and limitations in observational data can introduce some level of uncertainty in the results. Therefore, it is crucial to interpret the findings cautiously and consider the broader context when making decisions based on simulation outputs.

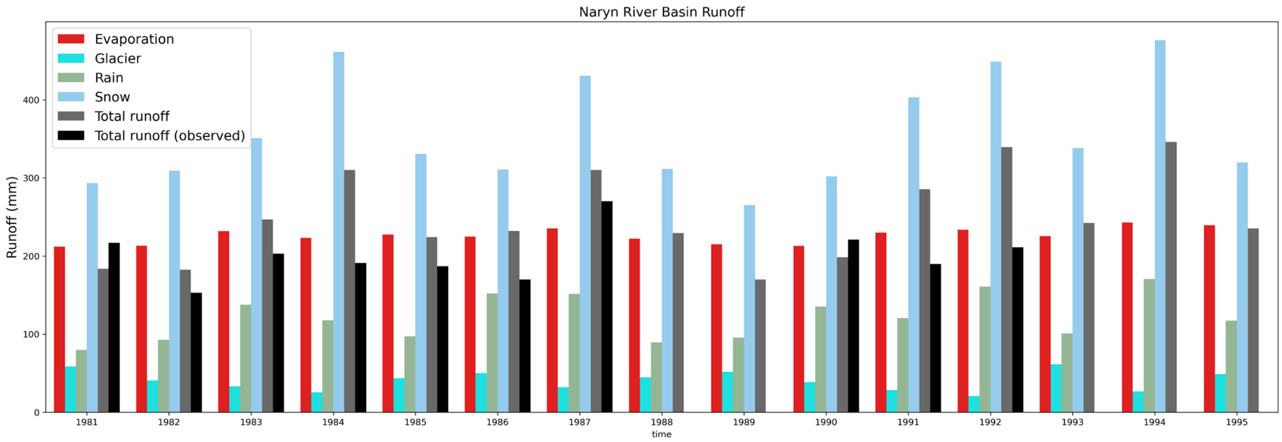

Figure 4.13 Naryn River Basin runoff components.

In our research, we initially focused on assessing the overall water balance of the Naryn River basin and compared the data with a gauge located at the inlet part of the Toktogul reservoir from 1981 to 1995 (Figure 4.13). This comparison allowed us to evaluate the accuracy of precipitation estimation based on the historical data provided by the NHRCM.

We observed that, on the whole, the water balance derived from our analysis coincided with the values obtained from the gauge, although there were some instances of underestimation. This suggests that the NHRCM historical data provides a reasonable estimation of precipitation in the Naryn River basin, albeit with a slight tendency to underestimate the actual values. It is important to note that the Naryn River basin consists of numerous mountain ranges, each of which may exhibit different precipitation patterns and amounts. Therefore, understanding the distribution and variability of precipitation across these mountainous regions is crucial for accurately assessing the water balance.

From our analysis, we have identified the crucial role of snow in the basin's water balance. Snow accumulation and subsequent melt contribute significantly to the overall runoff, especially during the spring and early summer months. The seasonal variation in snowmelt has a substantial impact on the river flow and water availability in the basin.

While snow plays a dominant role, glaciers also contribute to the water balance, particularly during the summertime when meltwater from glaciers becomes more significant. However, their contribution to the annual water balance is relatively smaller compared to snowmelt and other sources. The relationship between precipitation and glacier melt, as discussed in a previous section, is evident in our findings.

Understanding the dynamics and interactions between precipitation, snow, and glacier melt is essential for accurately predicting the water availability in the Naryn River basin. These components form a complex system, and the interplay between them can determine the overall water balance and hydrological processes in the region.

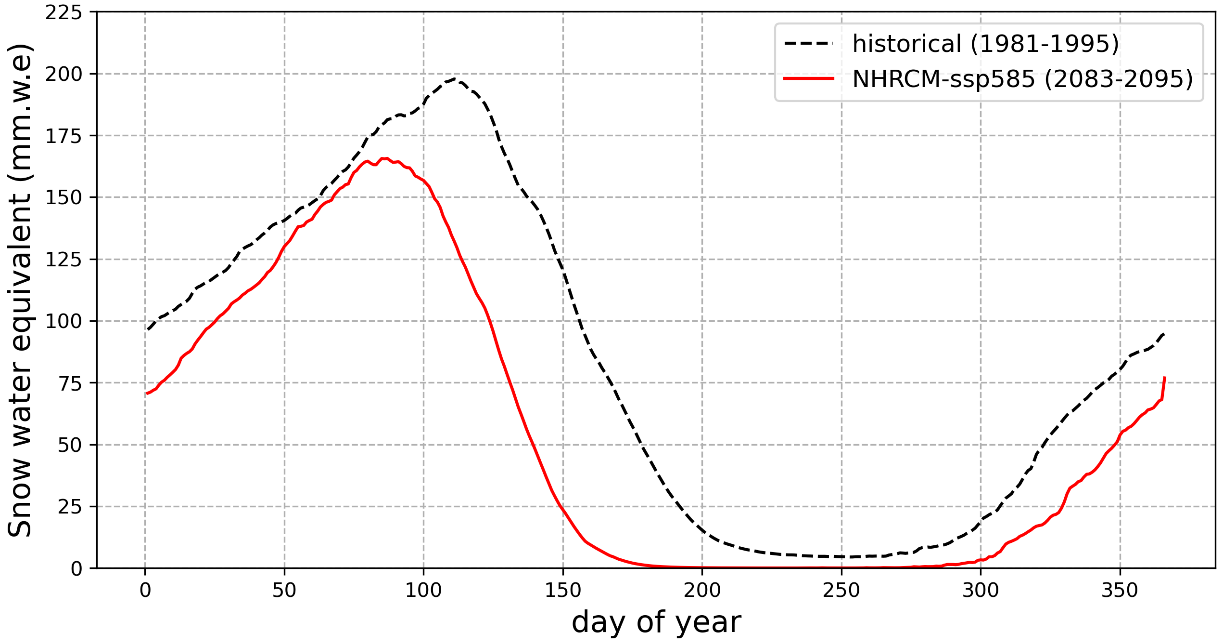

Figure 4.14 Seasonal changes of mean snow water equivalent across Naryn River Basin considering climate change scenario.

In our analysis, we examined the changes in snow water equivalent (SWE) using the regional model for both historical and future scenarios (Figure 4.14). For the historical period from 1981 to 1995, we observed that the peak of snow accumulation, typically in the second half of April, with approximately 200 mm of SWE, was shifted by 26 days to the end of March. This indicates a shift in the timing of peak snow accumulation due to climate change.

Furthermore, the maximum changes relative to the historical scenario were observed during the peak of snowmelt in May. During this period, we found that the maximum change in SWE reached 100 mm, indicating a potential decrease in water runoff from snowmelt. On average, we observed a reduction of 17% in the peak values of SWE compared to historical levels. Another important finding is the significant reduction in the volume of snow during the spring and summer periods. Historically, there has been a certain volume of water preserved, particularly in higher accumulation zones. However, in the simulations that consider climate change, the snow cover during this period is almost absent.

It is important to acknowledge that despite our efforts to use accurate meteorological data, there may be some uncertainty in the results of our simulations. While the radiation component plays a significant role in snow processes in this model system, input data may impact the accuracy of results. Therefore, while our analysis provides valuable insights into the changes in snow water equivalent and their potential implications, it is crucial to interpret the findings cautiously and consider the limitations and uncertainties associated with the meteorological data used in the simulations.

We conducted an analysis of snow water equivalent (SWE) distribution and amount across the study area. We compared historical data from the period of 1981-1995 with projected data for the years 2083-2095, examining each month individually. From the Figure 4.15 presented, it is evident that there is a slight deviation in SWE during winter months due to the presence of negative temperatures. In these colder months, snow accumulation is expected, resulting in higher SWE values. However, as we move into early spring and summer, when positive temperatures dominate in the lowland areas, melting rates tend to increase. This can be attributed to a combination of two main factors: reduced snow accumulation during winter and the influence of warmer temperatures. The Figure 4.15b clearly illustrates the impact of climate change on snow accumulation in the study area. The projected values for 2083-2095 indicate a significant decrease in snow accumulation, particularly during the months of April, May, and June. These months are highly affected by the changing climate, with both reduced winter snowfall and increased temperatures contributing to the decline in SWE.

The scale used in the Figure 4.16b represents the accumulation process in high altitudes, which, unfortunately, may not be observable in the future projections. This underscores the vulnerability of snow accumulation in the study area to climate change.

The implications of reduced snow accumulation during the critical months of April, May, and June are significant (Figure 4.15.4-6). Snowpack plays a crucial role in maintaining water availability in many regions, particularly during the dry season. The decline in SWE observed in the future projections suggests potential challenges for water resources, agriculture, and ecosystems that rely on the gradual release of meltwater from snowpack.

The findings of our analysis highlight the need for proactive measures to address the potential impacts of reduced snow accumulation. This could include implementing water management strategies that account for changing snowmelt patterns, promoting water conservation practices, and diversifying water sources to mitigate the potential water scarcity risks. Furthermore, the implications of decreased snow accumulation extend beyond the immediate water availability concerns. Snowpack acts as a natural reservoir, storing water throughout the winter months and releasing it gradually during the warmer seasons. This gradual release is vital for maintaining streamflow, supporting ecosystems, and ensuring a stable water supply for various human activities.

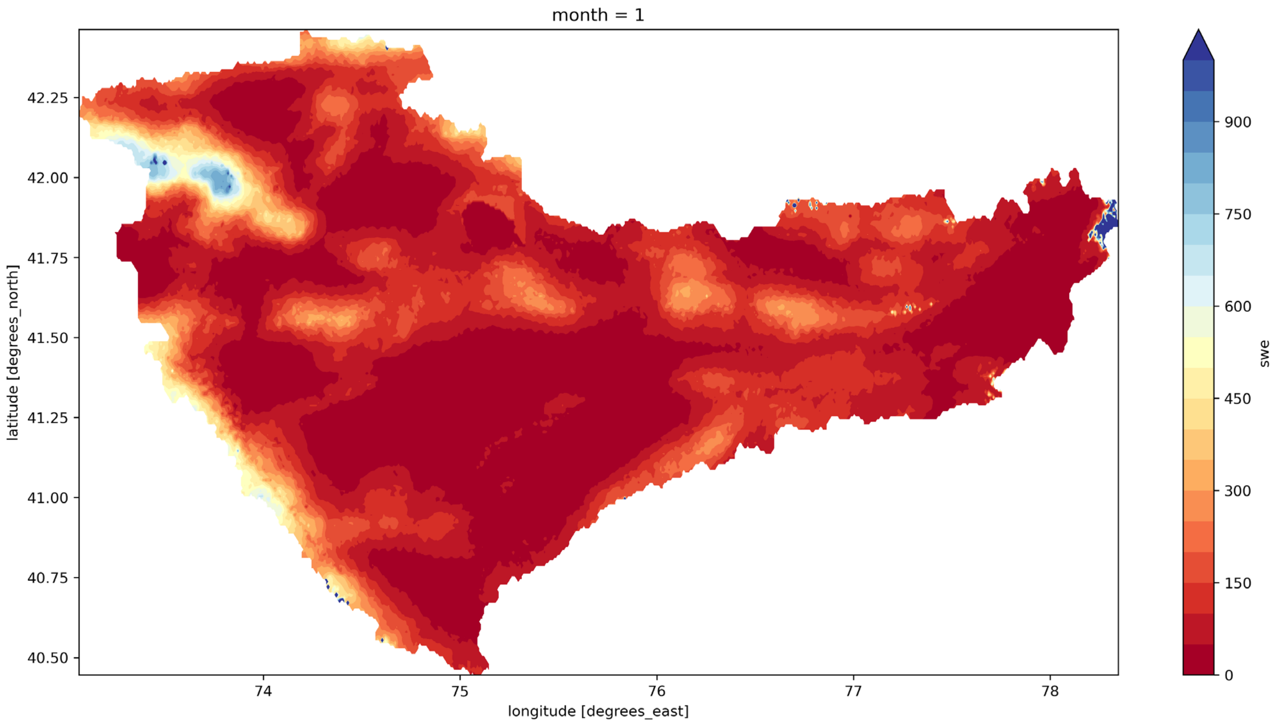

Figure 4.15.1a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for January month.

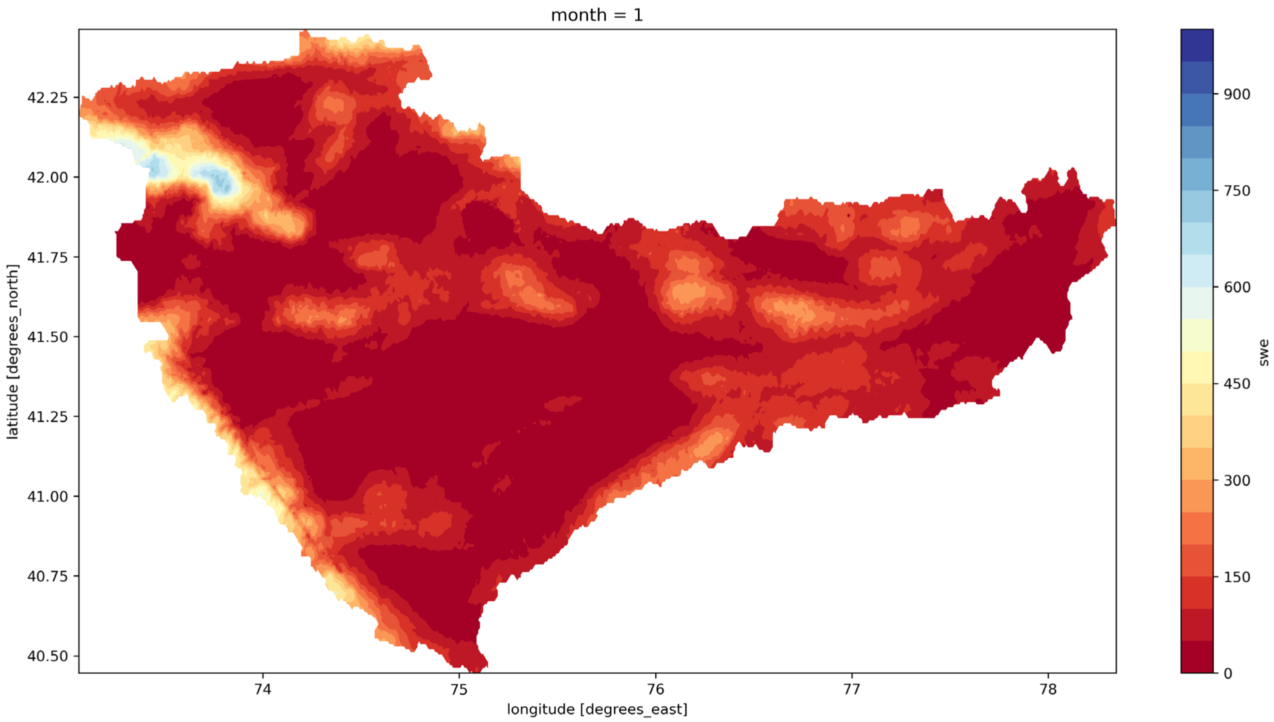

Figure 4.15.1b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for January month.

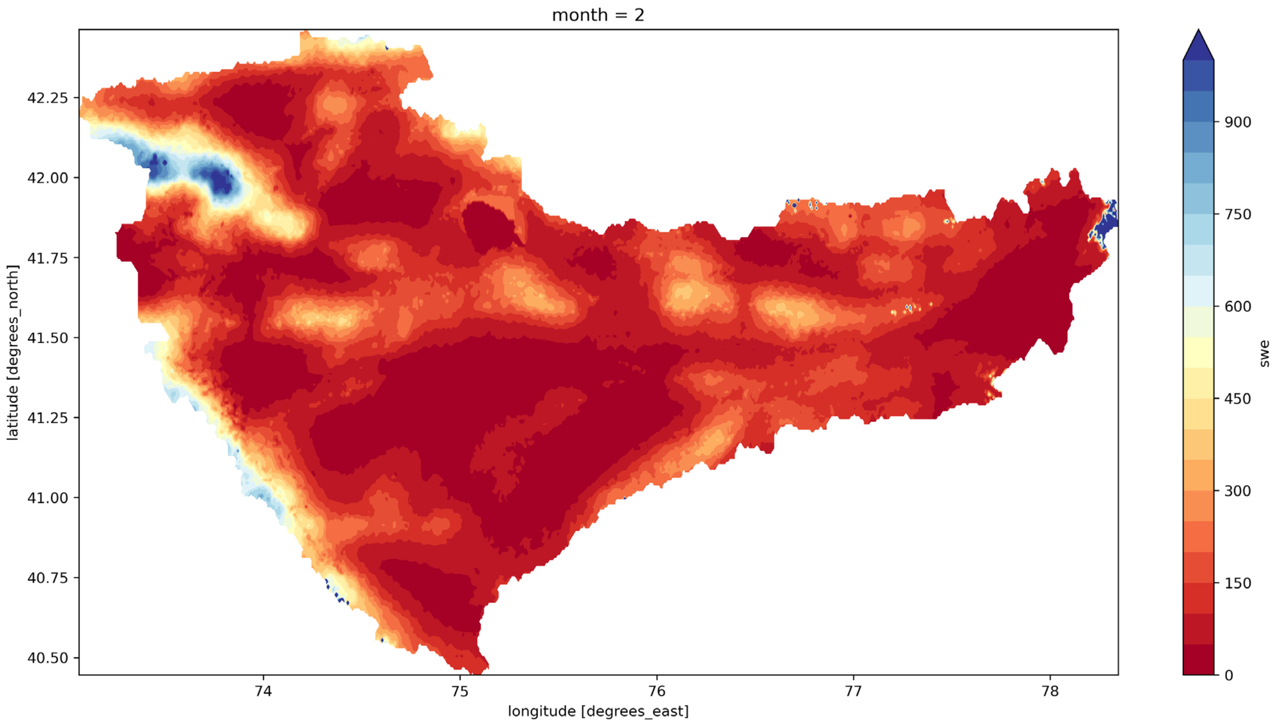

Figure 4.15.2a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for February month.

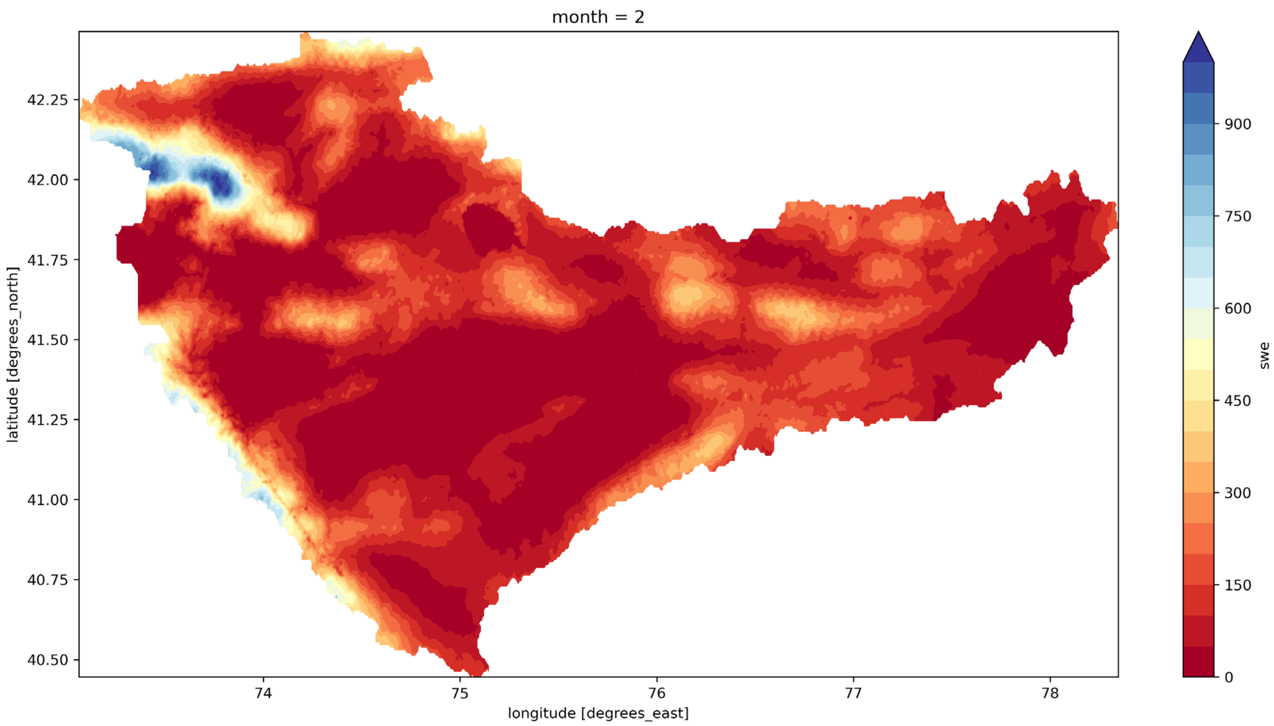

Figure 4.15.2b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for February month.

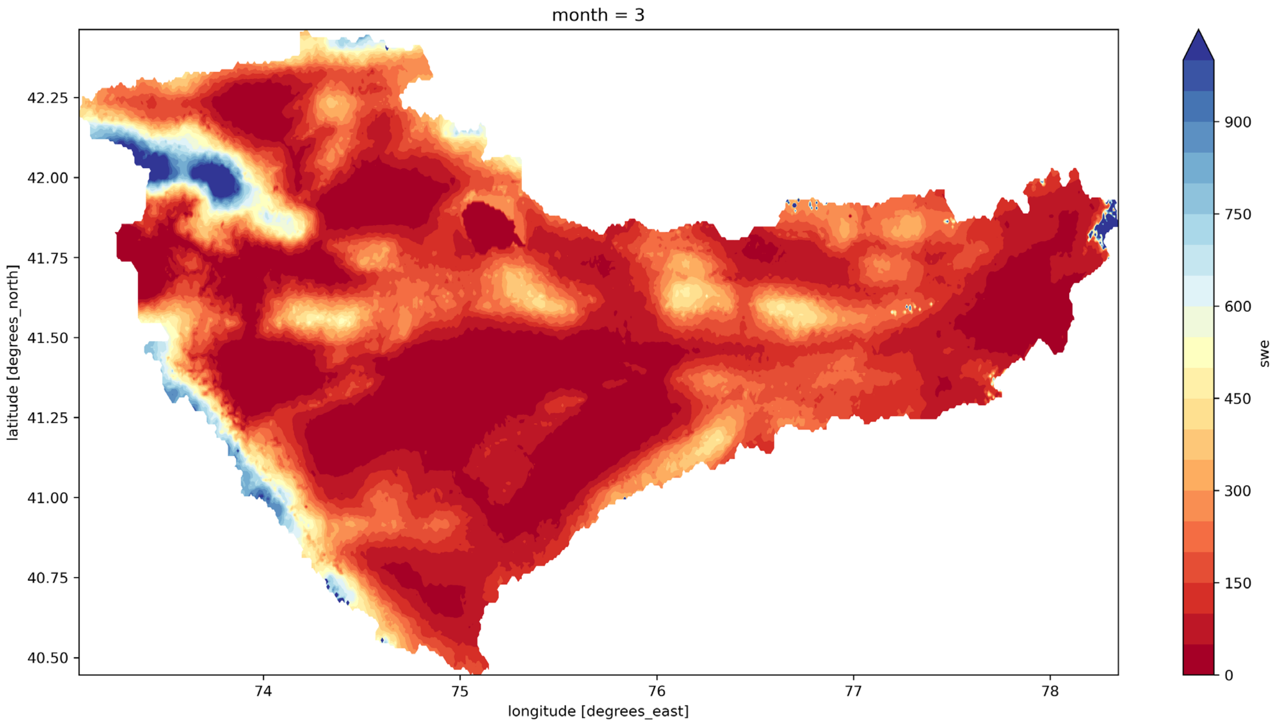

Figure 4.15.3a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for March month.

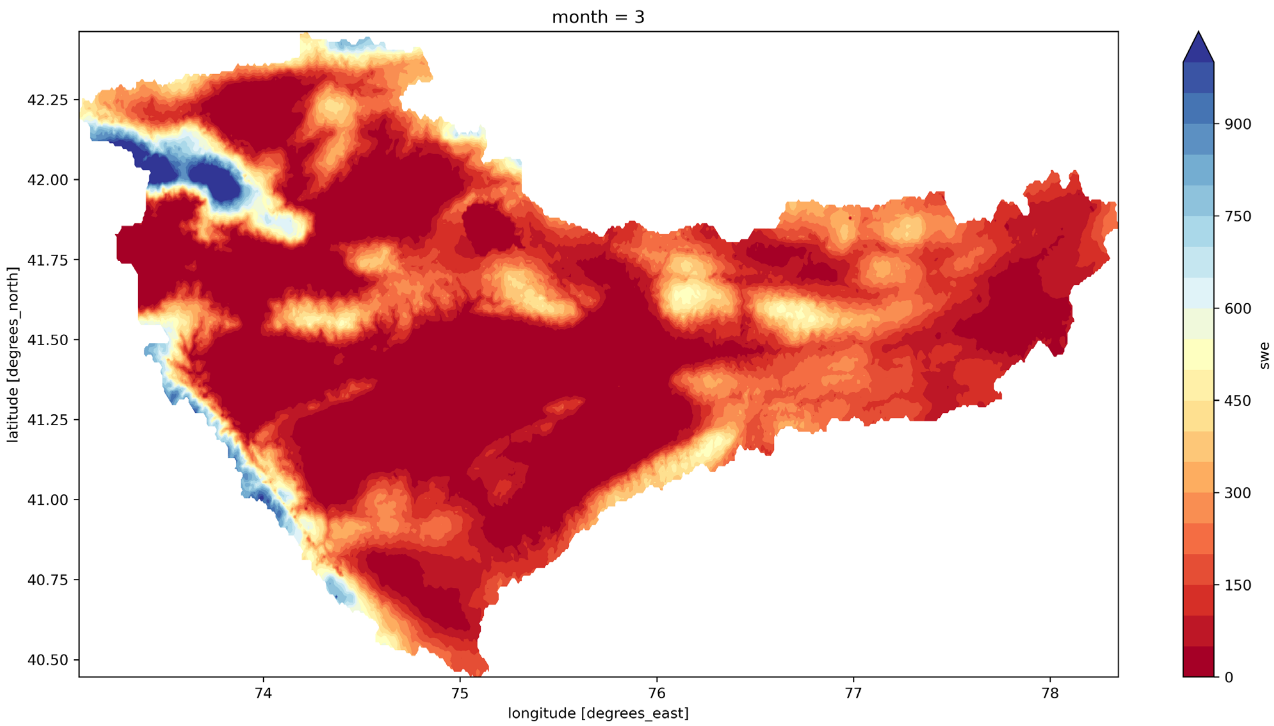

Figure 4.15.3b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for March month.

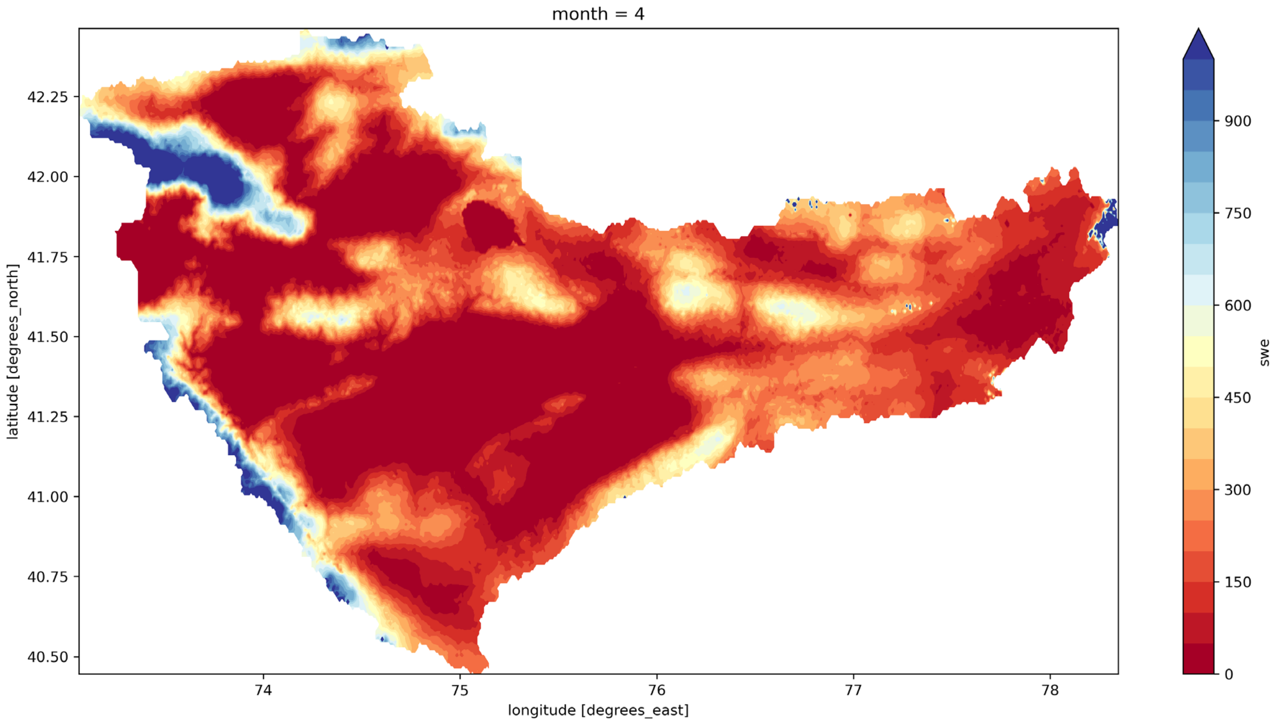

Figure 4.15.4a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for April month.

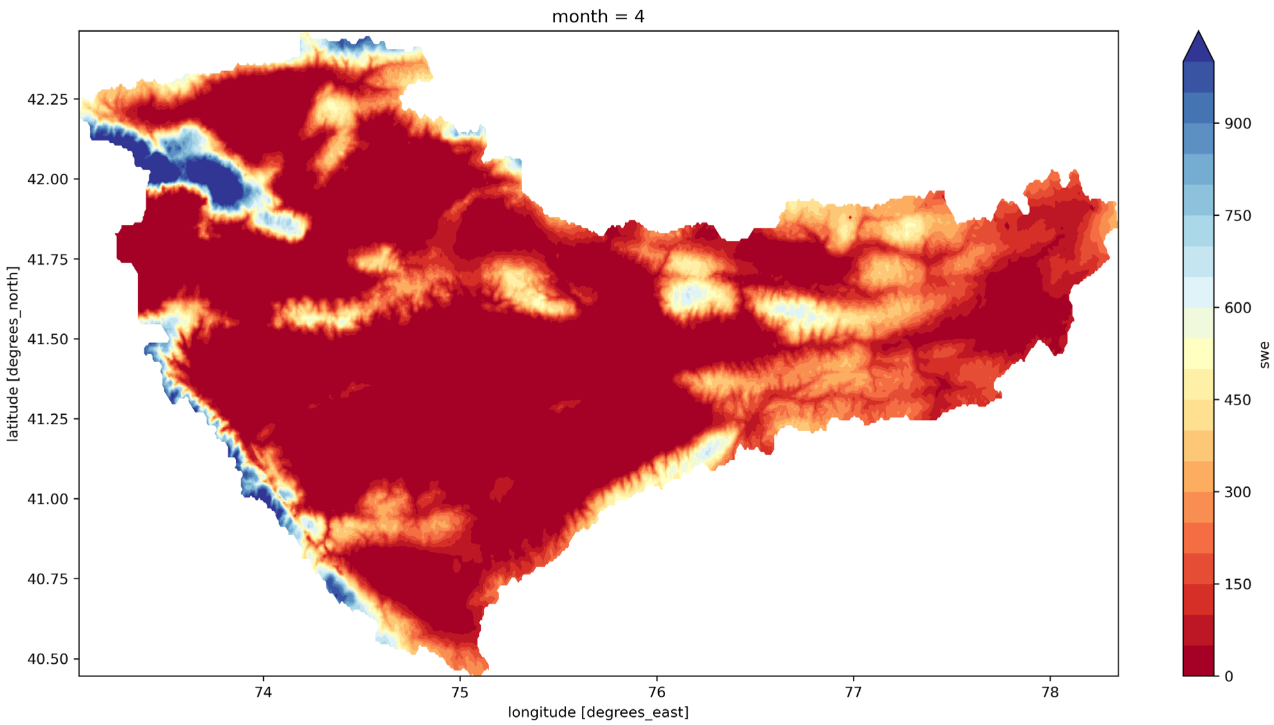

Figure 4.15.4b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for April month.

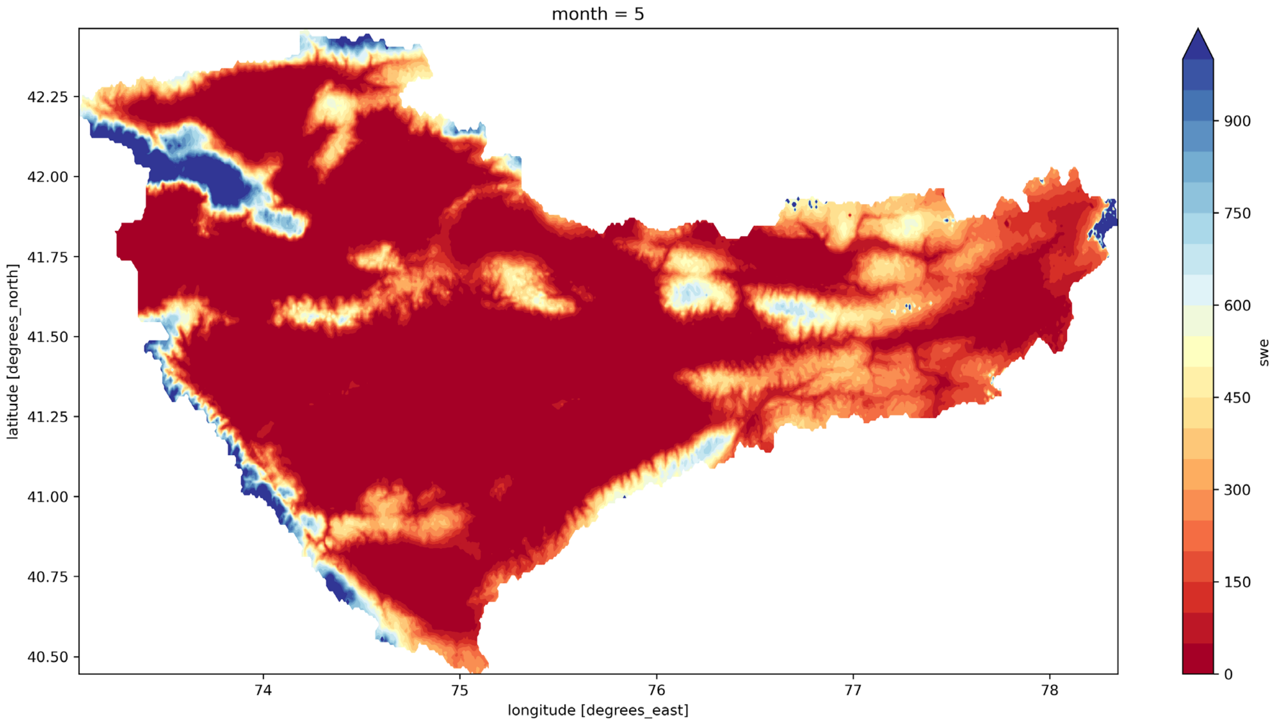

Figure 4.15.5a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for May month.

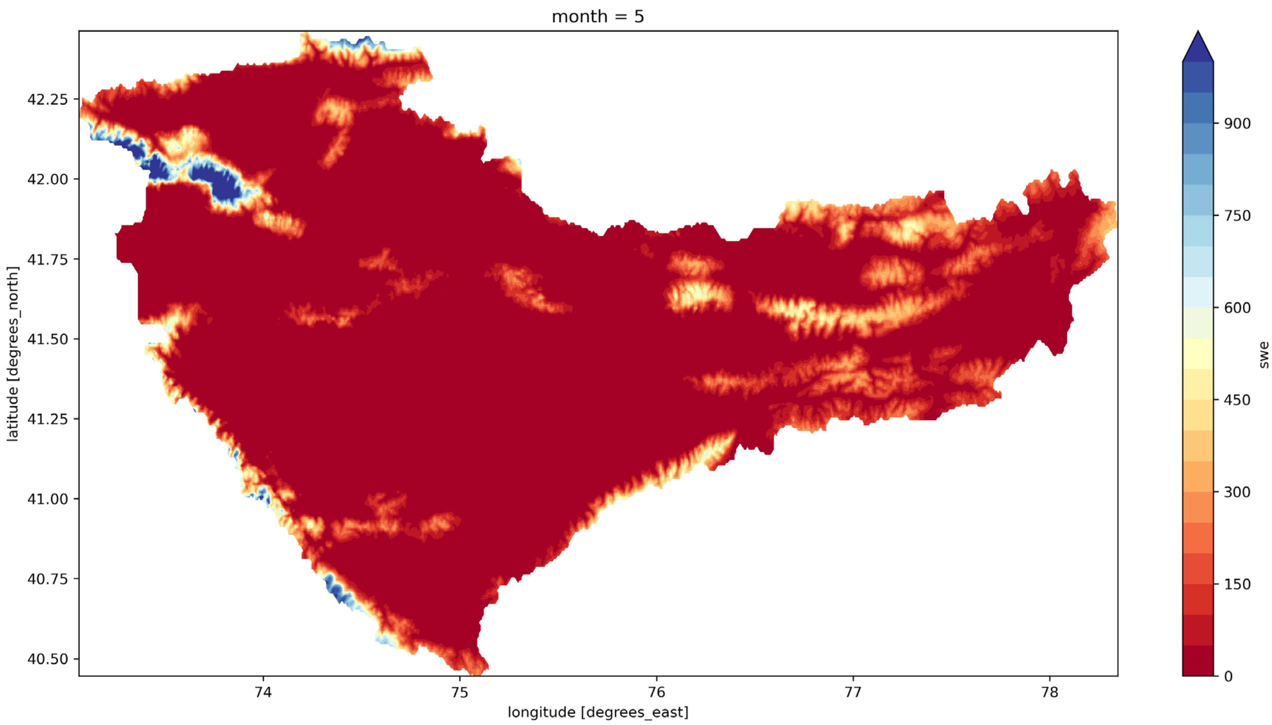

Figure 4.15.5b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for May month.

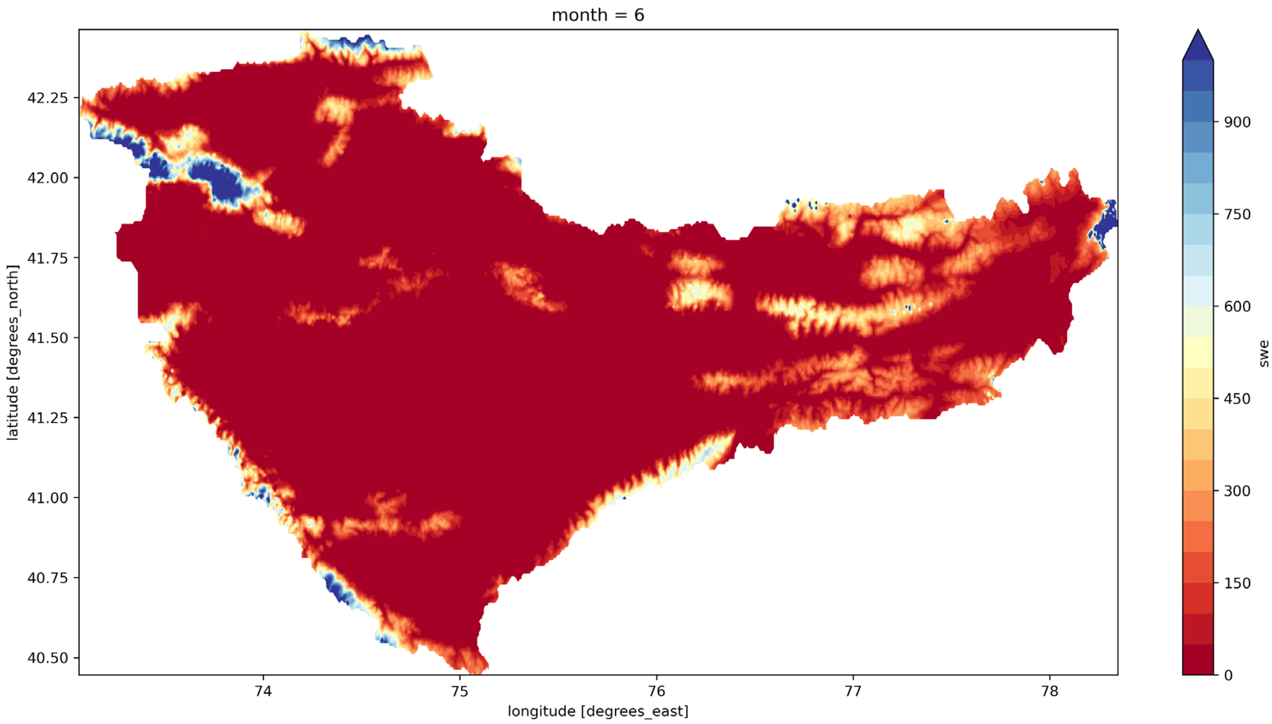

Figure 4.15.6a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for June month.

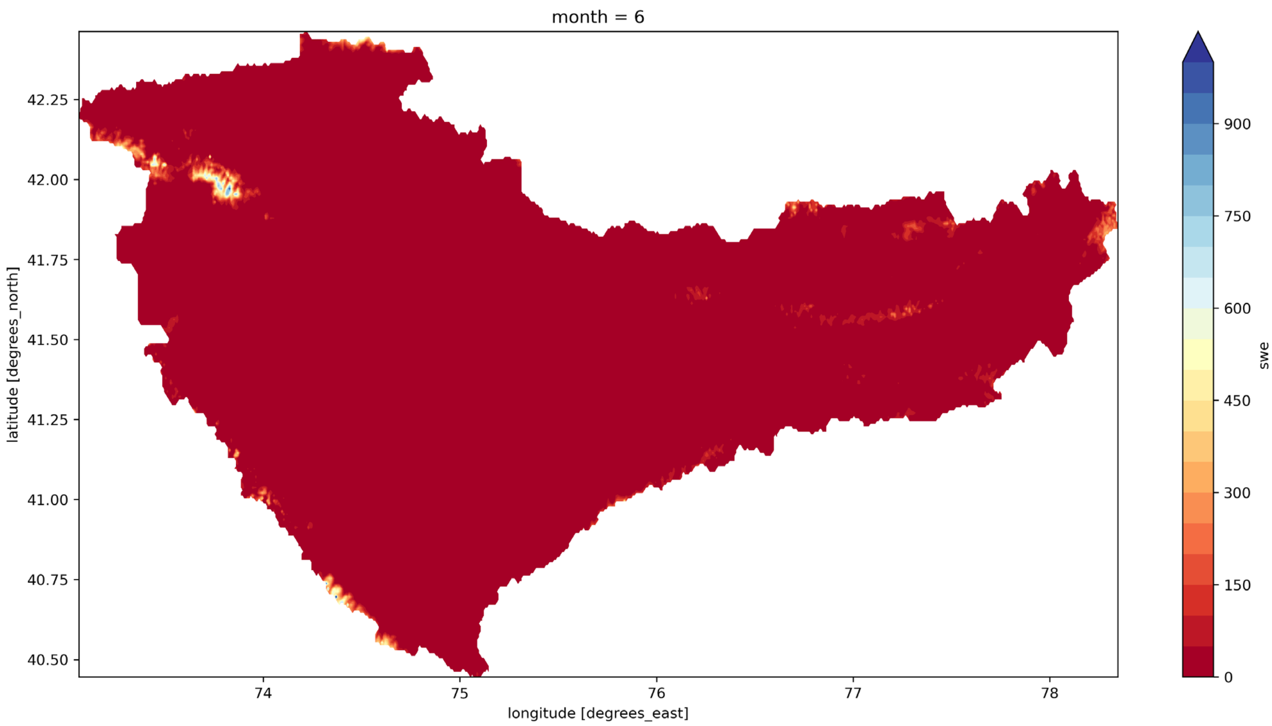

Figure 4.15.6b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for June month.

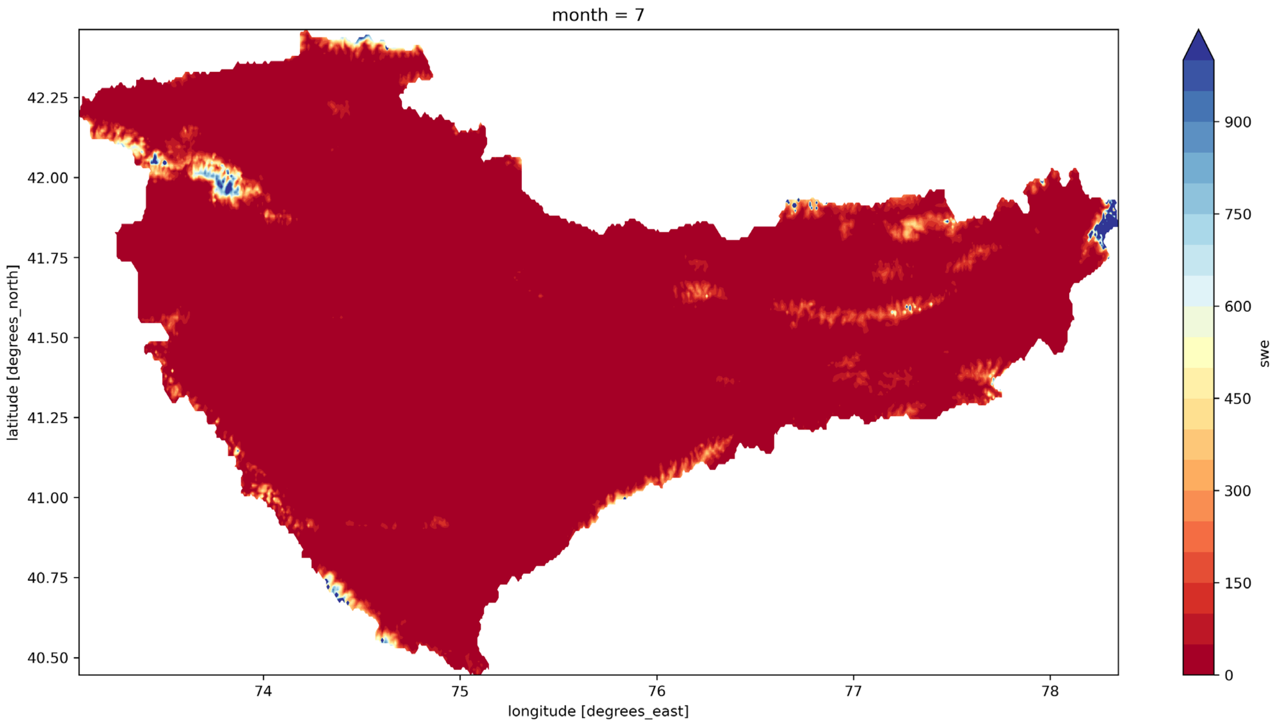

Figure 4.15.7a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for July month.

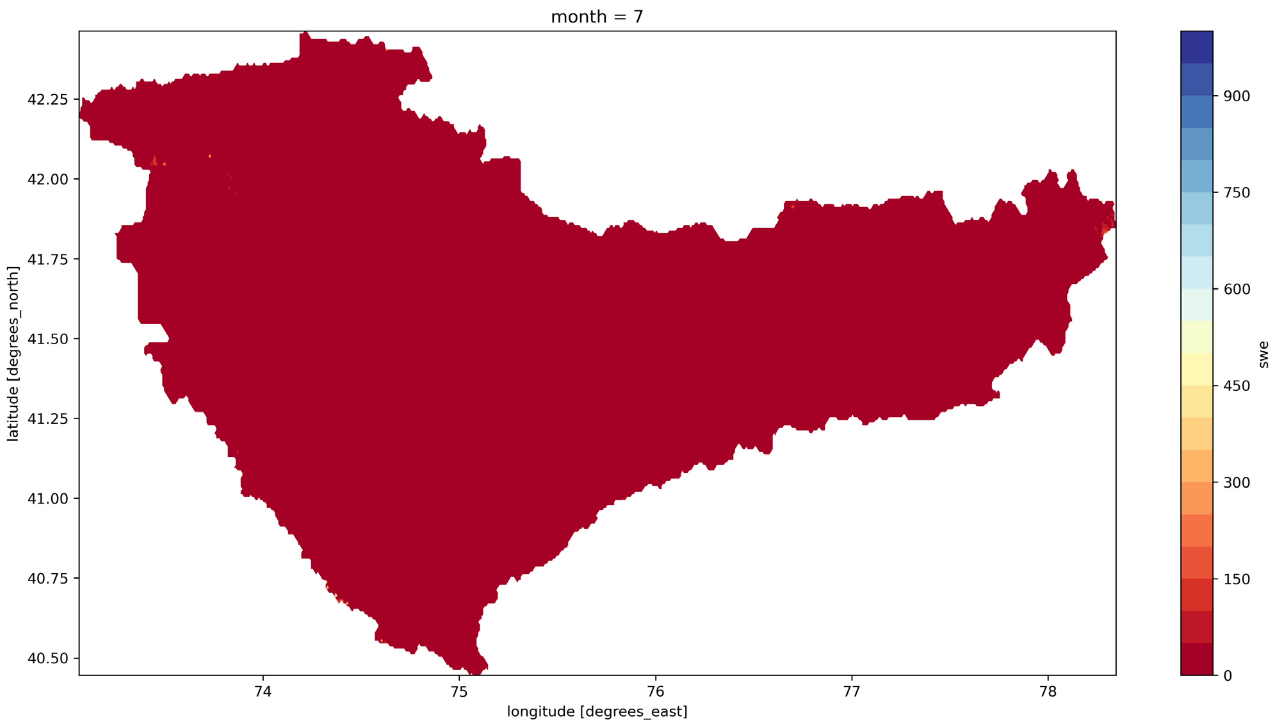

Figure 4.15.7b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for July month.

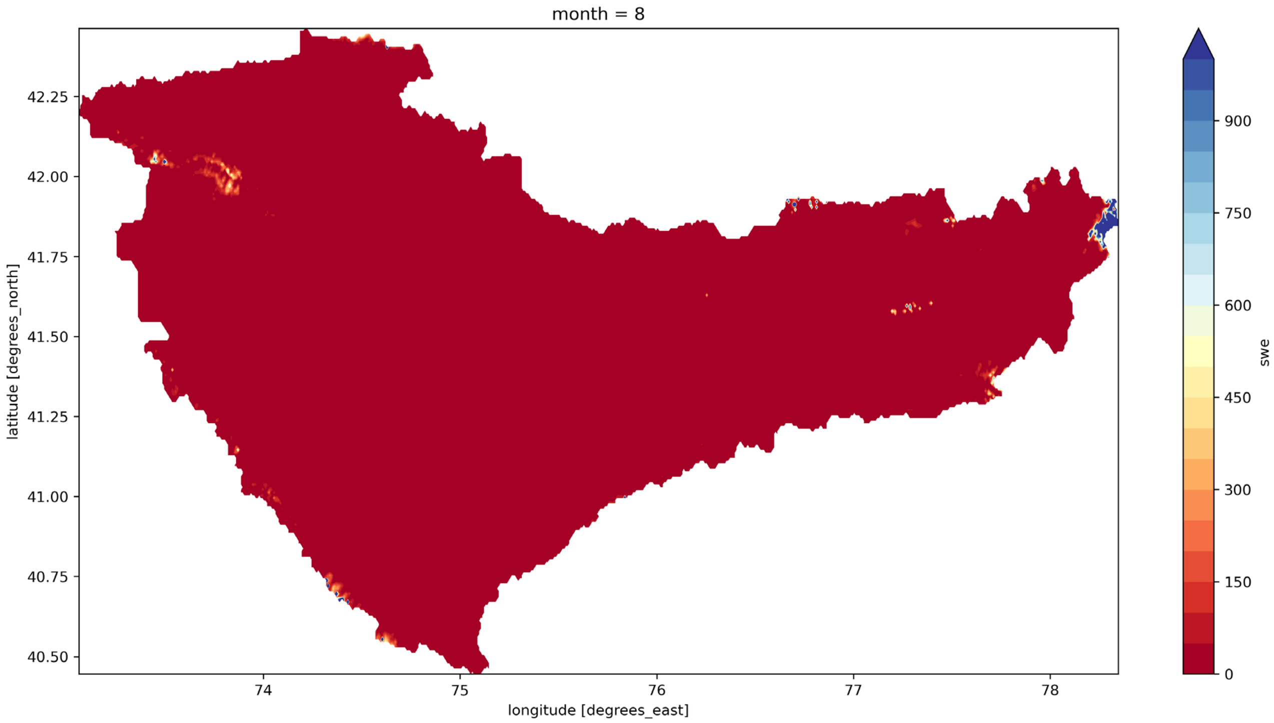

Figure 4.15.8a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for August month.

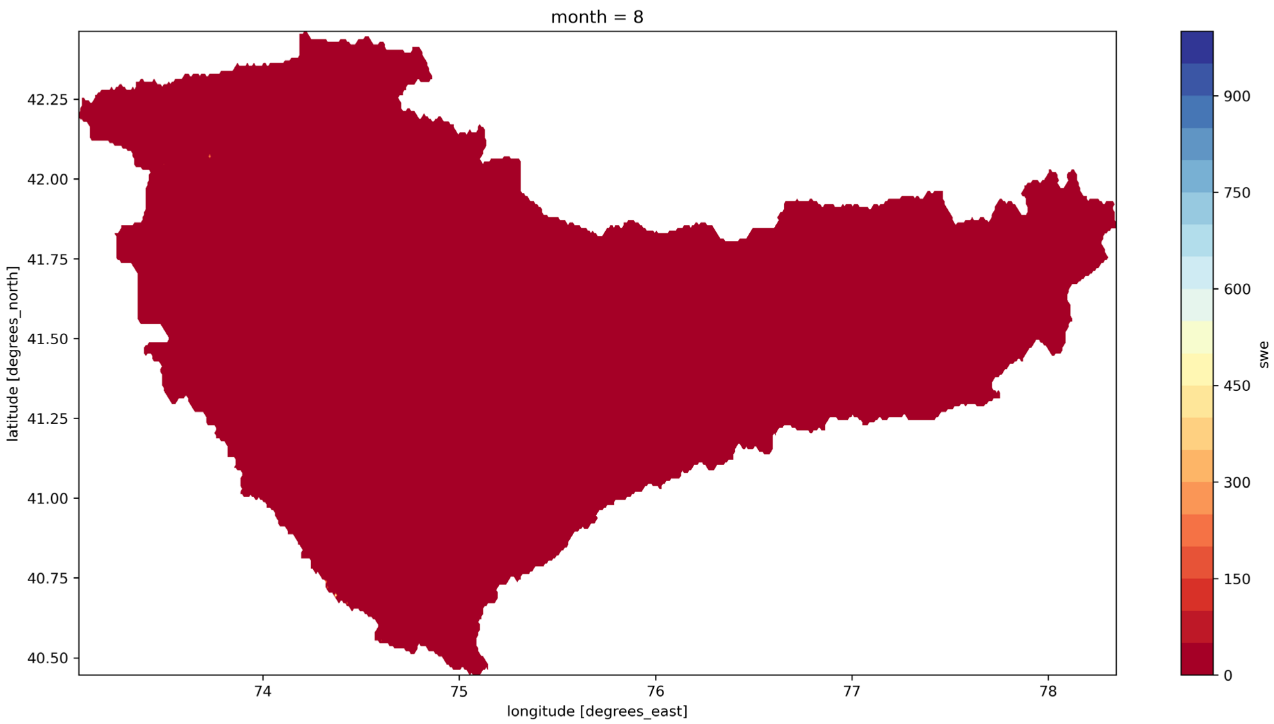

Figure 4.15.8b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for August month.

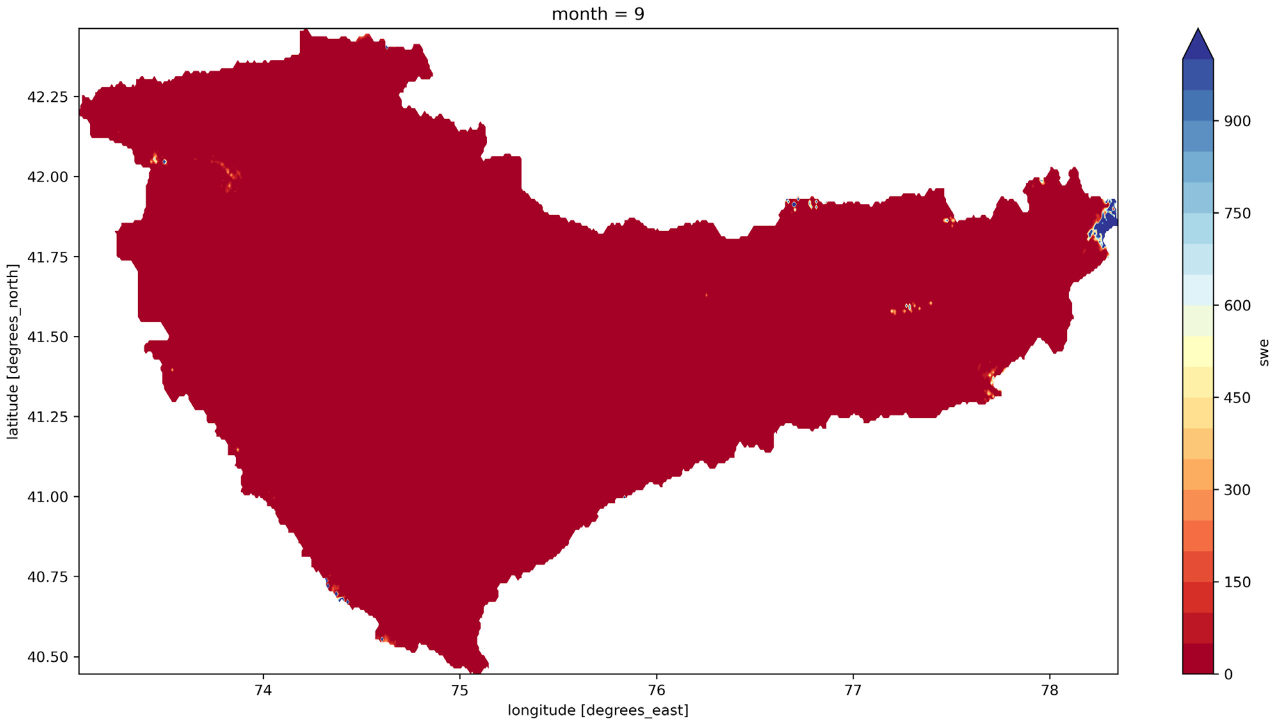

Figure 4.15.9a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for September month.

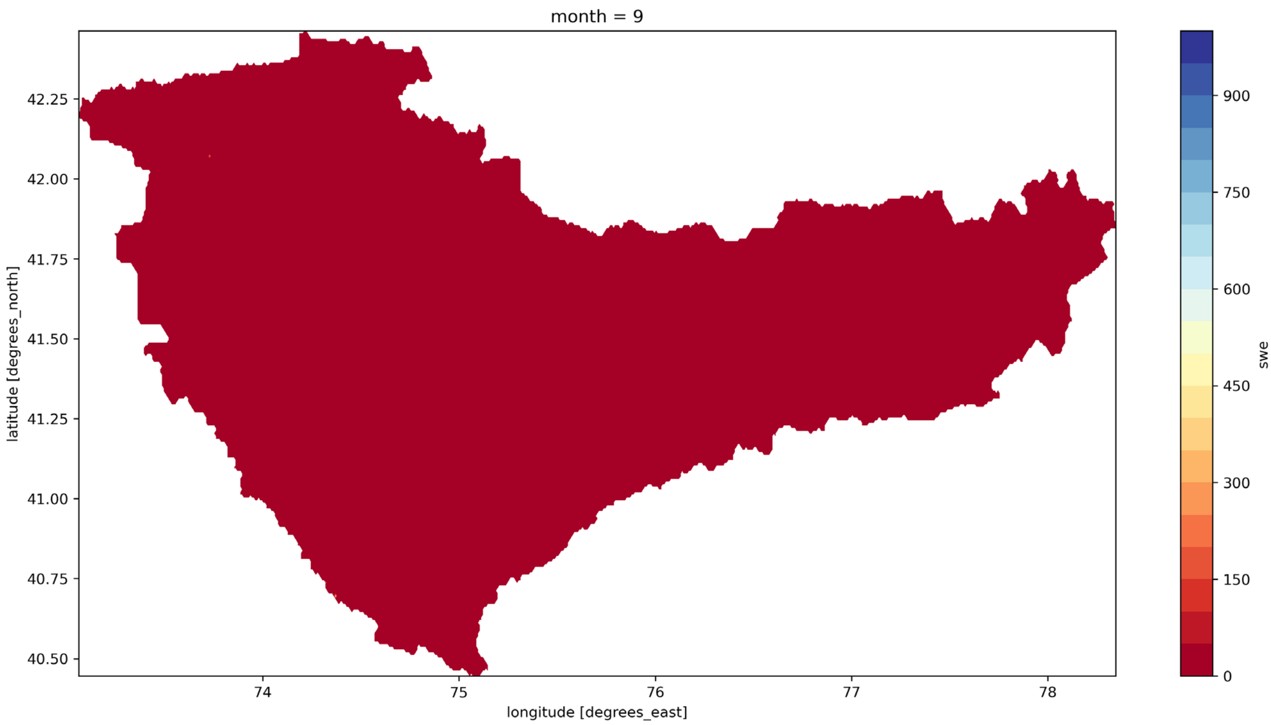

Figure 4.15.9b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for September month.

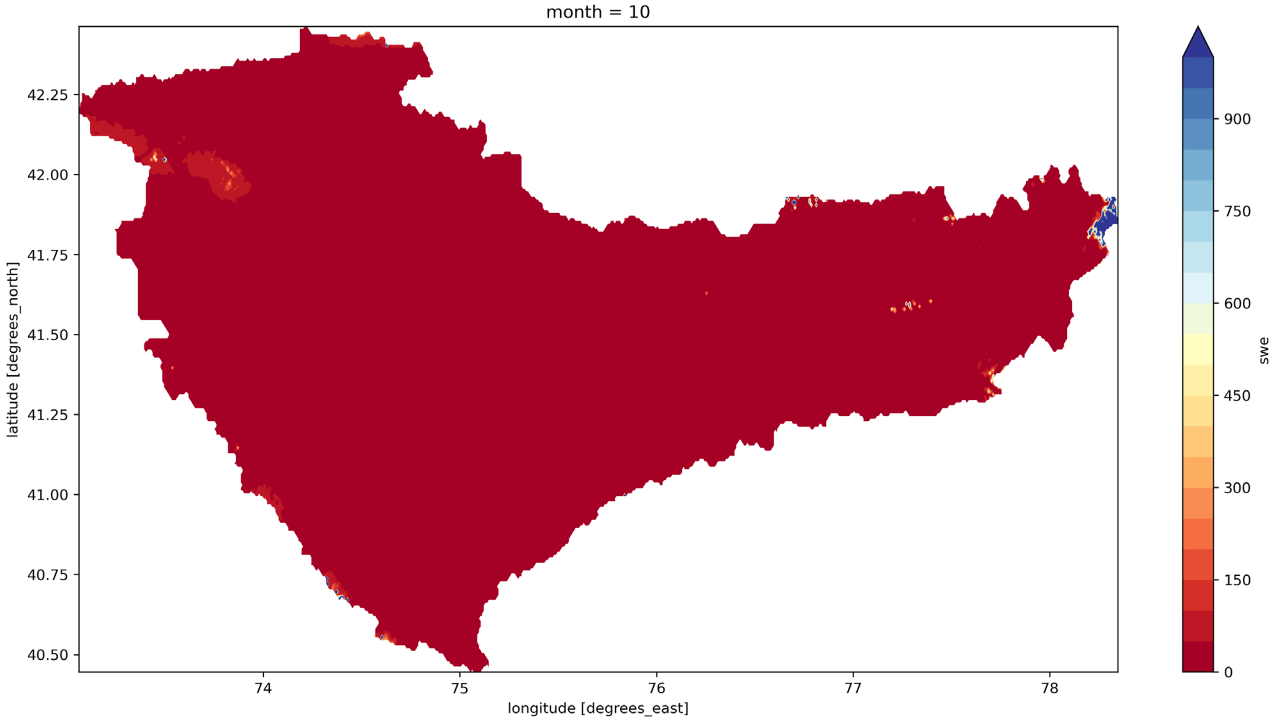

Figure 4.15.10a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for October month.

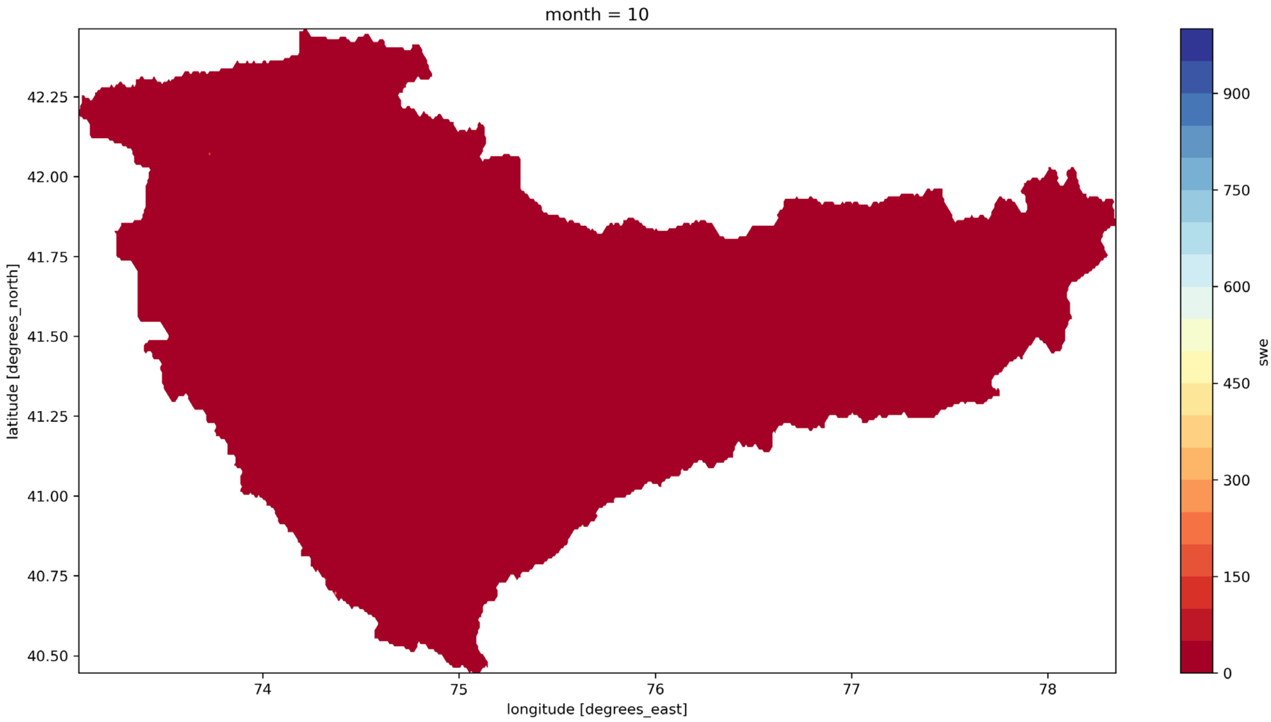

Figure 4.15.10b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for October month.

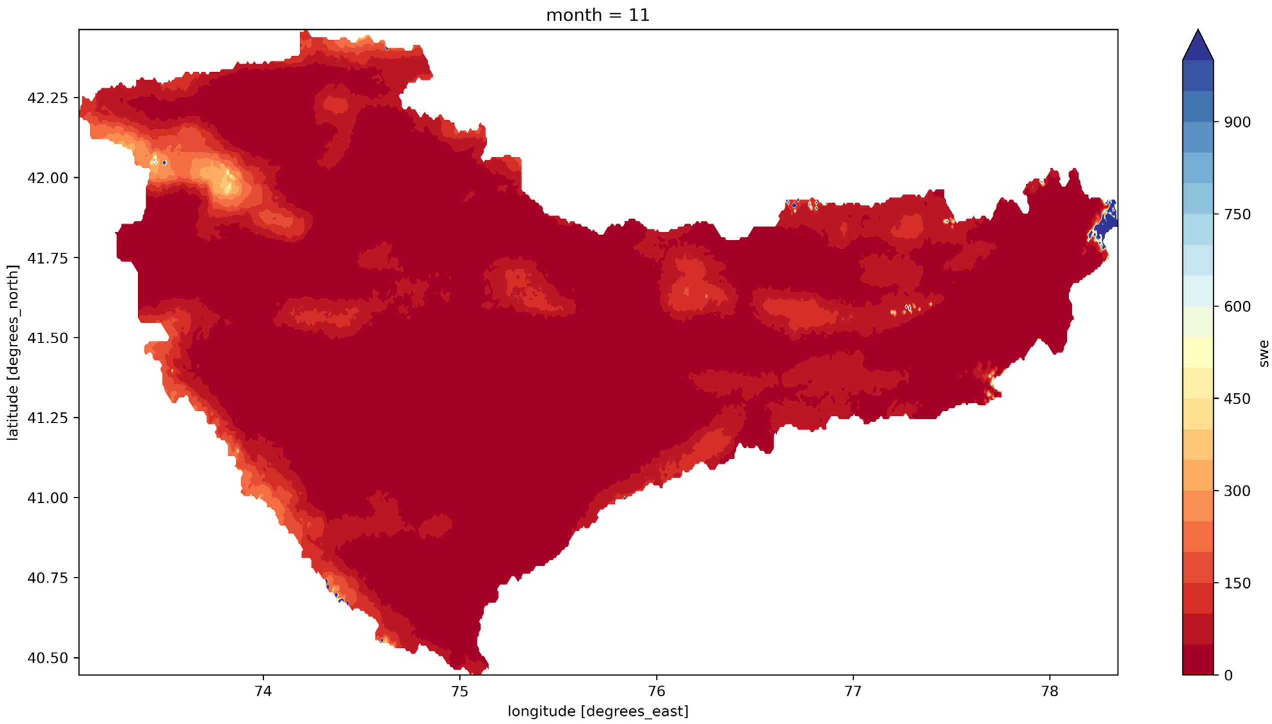

Figure 4.15.11a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for November month.

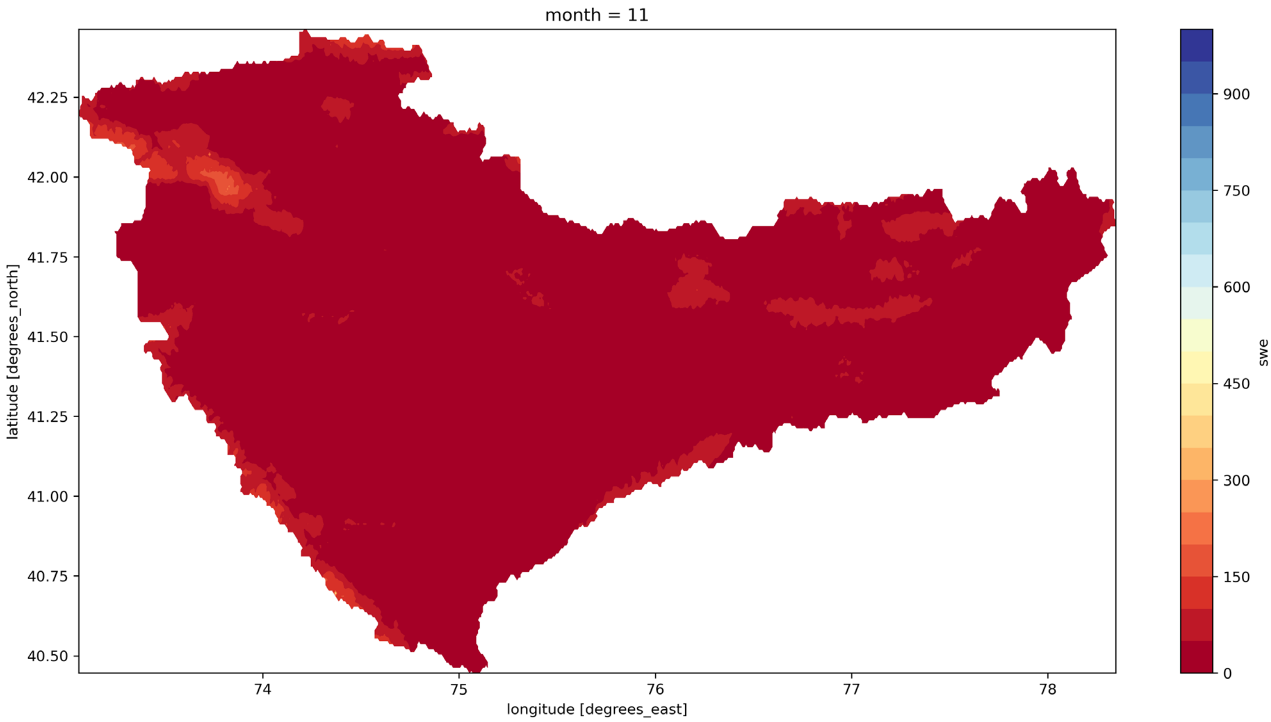

Figure 4.15.11b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for November month.

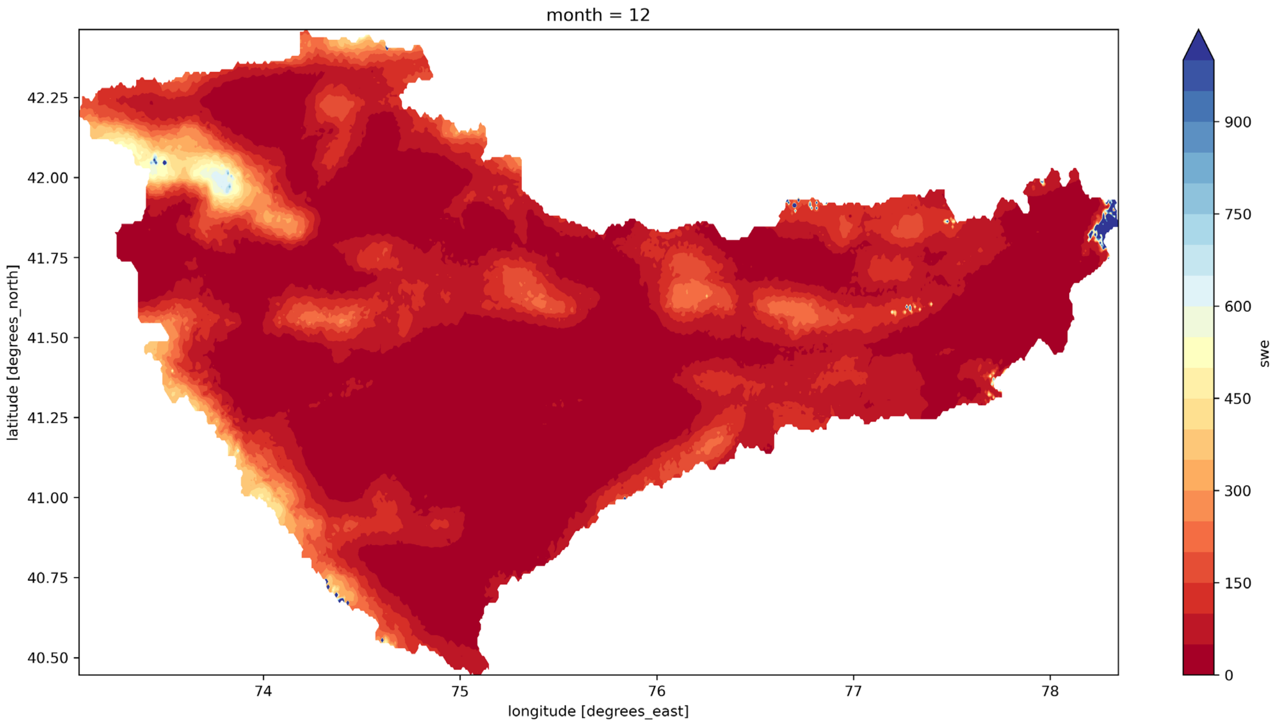

Figure 4.15.12a Snow water equivalent (swe, mm) distribution across Naryn River Basin. Historical mean values for December month.

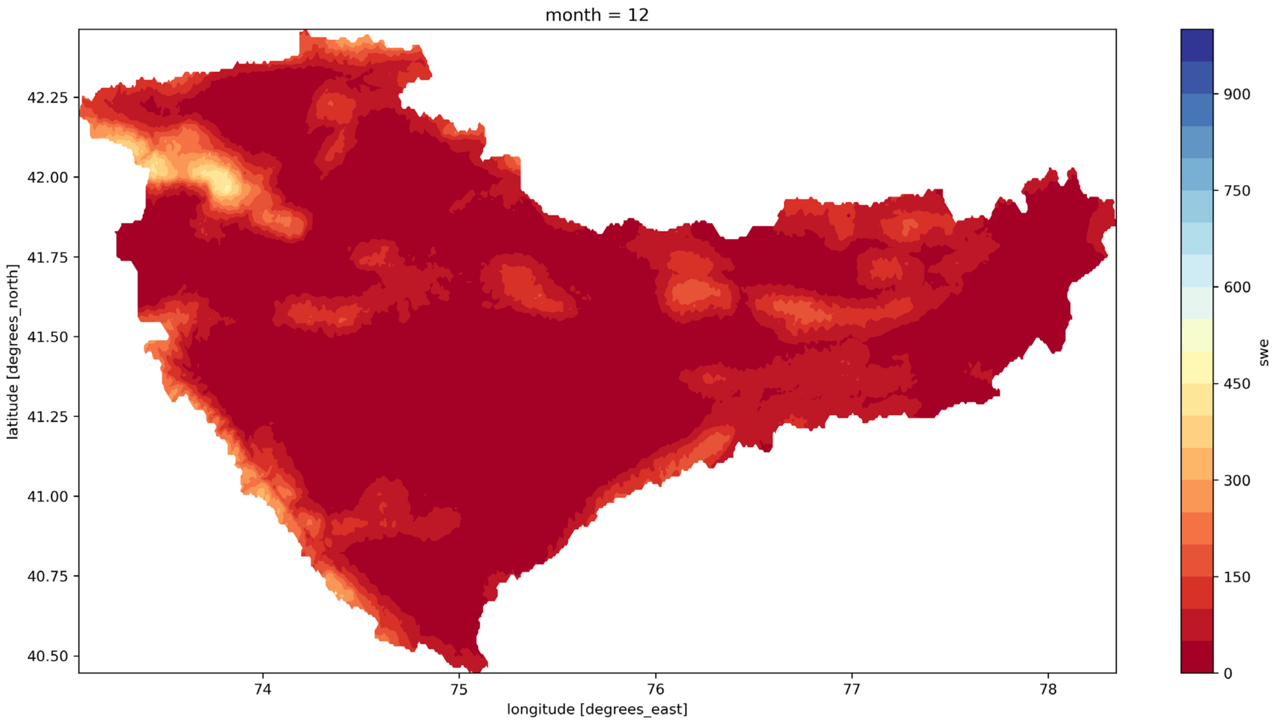

Figure 4.15.12b Snow water equivalent (swe, mm) distribution across Naryn River Basin. Projected mean values for December month.

The mass balance of a glacier refers to the equilibrium between two essential processes: accumulation and ablation. Accumulation refers to the addition of snow and ice to the glacier, typically through precipitation in the form of snowfall. Ablation, on the other hand, represents the loss of mass from the glacier, which can occur through various mechanisms such as melting, sublimation, and calving of icebergs into bodies of water.

The balance between accumulation and ablation is crucial for maintaining the overall mass of a glacier. When accumulation exceeds ablation, the glacier experiences a positive mass balance, meaning it gains more mass than it loses. This leads to an increase in glacier size and volume over time. Conversely, if ablation surpasses accumulation, the glacier undergoes a negative mass balance, resulting in a net loss of mass. This leads to glacier retreat and a reduction in size and volume.

Understanding the mass balance of a glacier is of utmost importance when assessing the health and behavior of glaciers. It provides valuable insights into the response of glaciers to climate change and allows scientists to quantify the contributions of glaciers to regional and global water resources. By measuring and monitoring the mass balance of glaciers, researchers can evaluate the impact of environmental factors, such as temperature, precipitation, and solar radiation, on glacier dynamics.

Positive mass balance indicates that a glacier is accumulating more snow and ice than it is losing, suggesting a healthy and growing glacier. This scenario is often associated with regions where winter snowfall exceeds summer melting. Glaciers with positive mass balance can act as a natural reservoir, storing water in the form of ice and gradually releasing it during the warmer months. This meltwater plays a crucial role in sustaining downstream ecosystems, supporting agriculture, and providing a reliable water supply for human populations.

Conversely, a negative mass balance signifies that a glacier is losing more mass through ablation than it is gaining through accumulation. This is typically the result of increased melting due to rising temperatures or reduced snowfall. Negative mass balance leads to glacier shrinkage, reduced ice volume, and decreased water availability in downstream areas. As glaciers retreat, the timing and magnitude of meltwater contributions to rivers and lakes can change, impacting water resource management, hydropower generation, and ecological systems that rely on glacier-fed water.

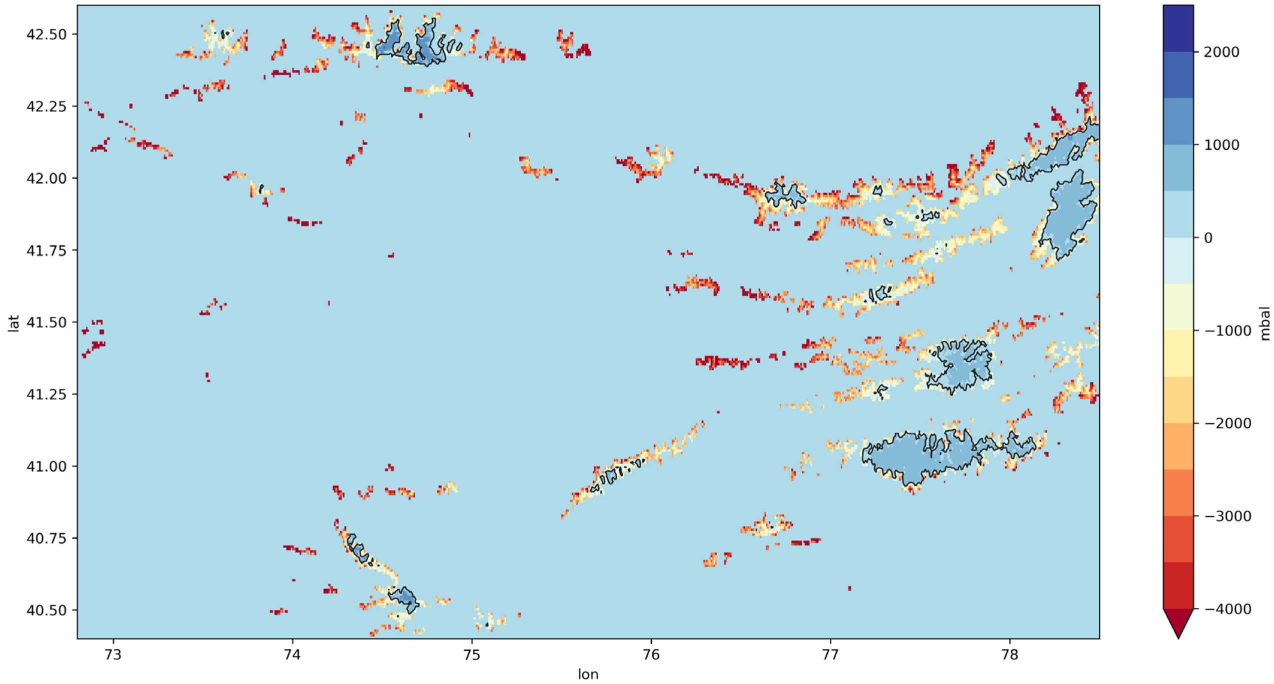

Figure 4.16a Mean historical glacier mass balance (mbal, mm) in a study domain.

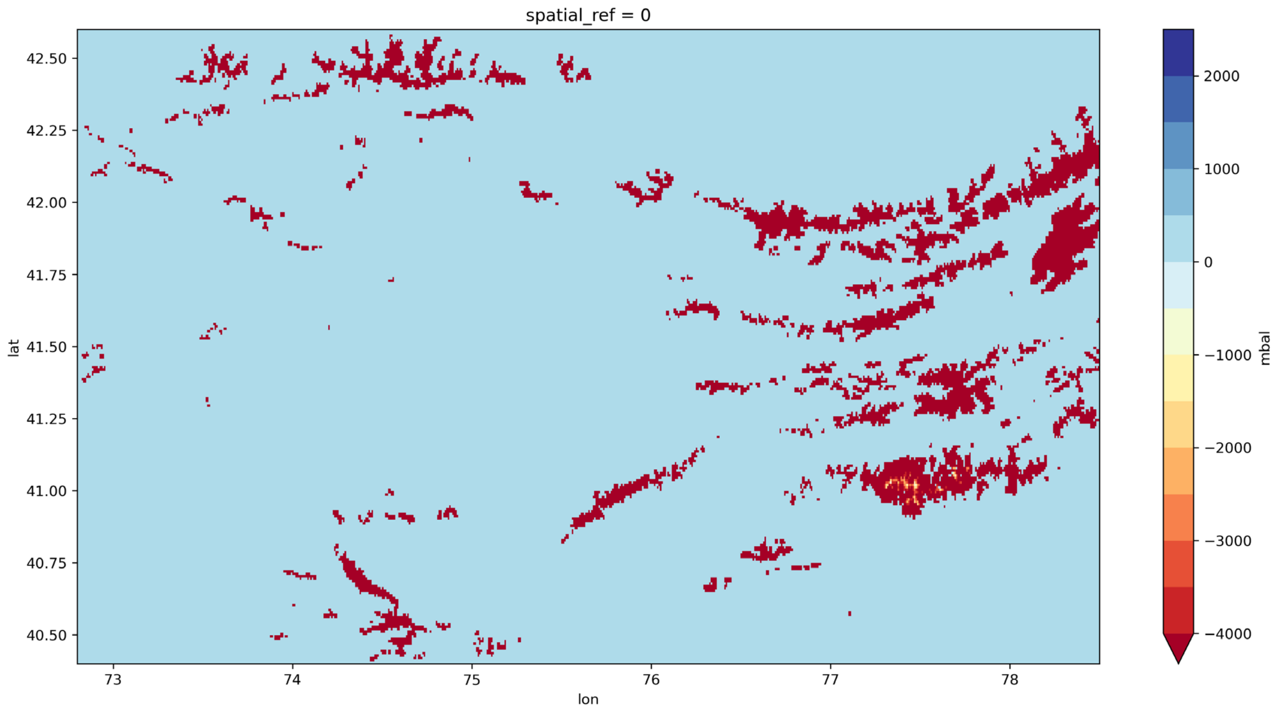

Figure 4.16b Mean projected glacier mass balance (mbal, mm) in a study domain.

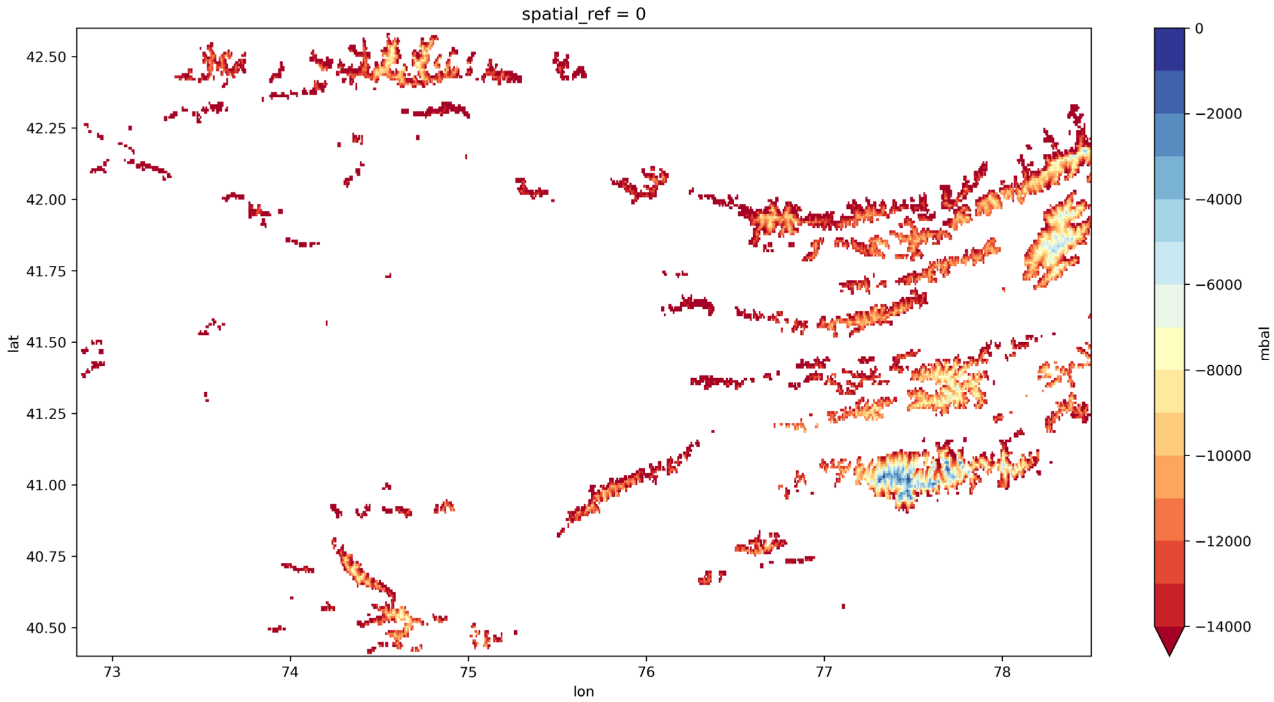

Figure 4.16c Mean projected glacier mass balance (mbal, mm, scaled) in a study domain.

The results of our glacier mass balance modeling reveal the significant and potentially alarming consequences of climate change in the region, considering the equilibrium state of the climate. It is important to note that in our modeling, we neglected glacier flow and assumed that the glacier area remained the same for both historical and future simulations. While this approach may introduce some uncertainties, it allows us to compare the suitability of future climate conditions for glaciated systems.

The Figure 4.16a representing the historical simulations of the Naryn River Basin clearly illustrates the equilibrium contour line, where accumulation and ablation are equal. In the lower parts of the glacier, where ablation is dominant, we observe melting of approximately 3000-4000mm during the season. However, the projected results depict a much higher magnitude of melting, reaching over 14000mm, as shown in the scaled version of the Figure 4.16c.

This significant increase in melting observed in the future projections highlights the vulnerability of glaciated systems to climate change. The higher temperatures and changing precipitation patterns anticipated in the future can have a profound impact on the mass balance of glaciers. The excessive melting observed in the projected results suggests a potential imbalance between accumulation and ablation, which can lead to accelerated glacier retreat and mass loss. Understanding the magnitude of melting and its spatial distribution is crucial for assessing the future sustainability of glaciated systems in the region. The excessive melting observed in the projected results raises concerns about the long-term viability of these systems and the potential implications for water resources, ecosystems, and communities dependent on glacier meltwater.

It is important to acknowledge that glacier mass balance modeling involves certain uncertainties. Factors such as the representation of surface processes, snowfall variability, and the accuracy of climate projections can influence the reliability of the results. Therefore, caution must be exercised when interpreting and extrapolating the findings.

Nevertheless, the dramatic consequences of climate change evident in our modeling results emphasize the urgent need for comprehensive strategies to mitigate and adapt to these changes. Efforts to reduce greenhouse gas emissions, promote sustainable practices, and implement adaptive water management strategies are crucial for safeguarding the fragile glaciated systems and the services they provide.

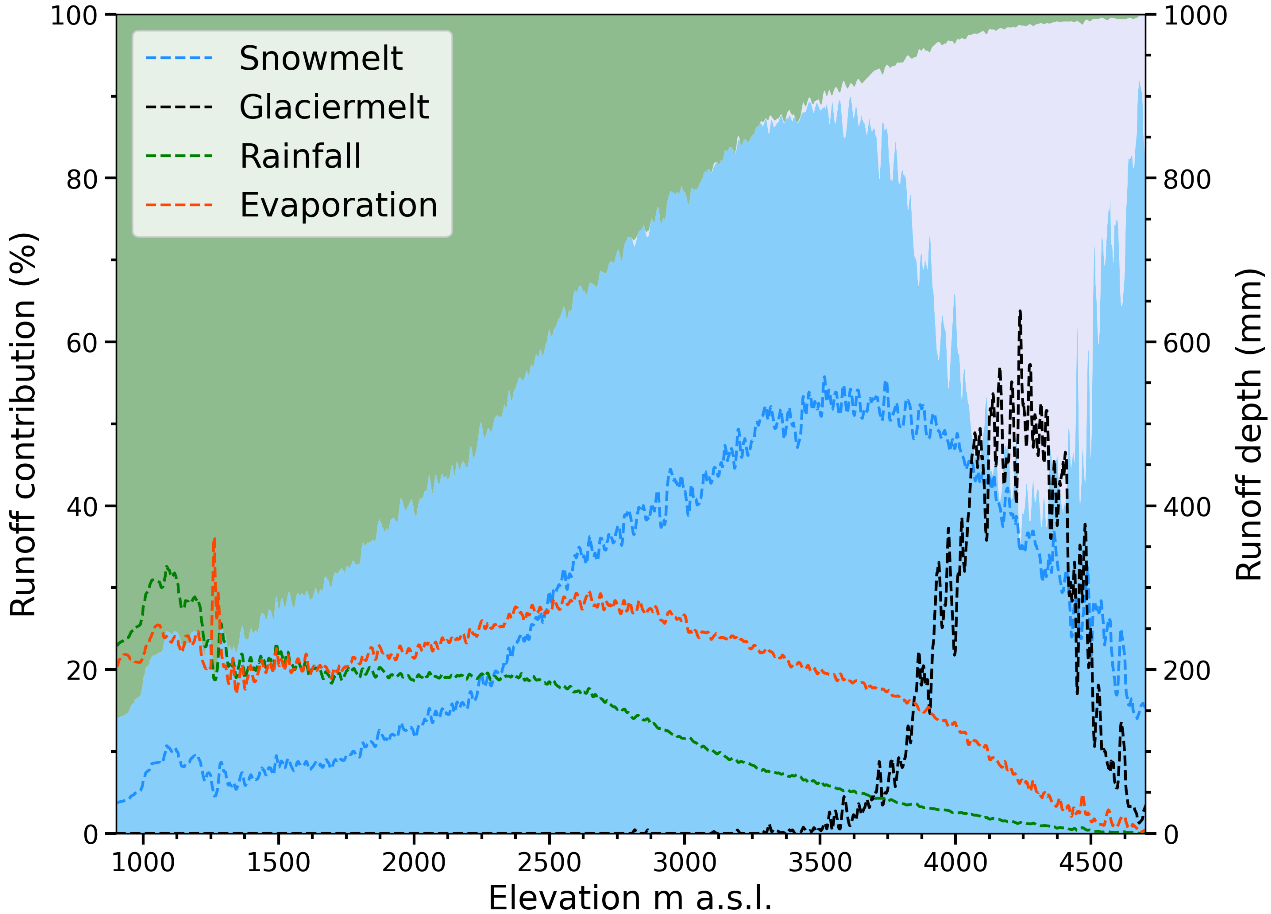

Figure 4.17 Runoff components along elevation in Naryn River Basin (historical).

In our analysis of the annual distribution of runoff results across elevations, we observed significant changes in the generated runoff considering various sources, as depicted in the figure (Figure 4.17). When comparing these results to the projected climate change scenarios (Figure 4.18), we noted a notable shift in the contribution of snowmelt runoff in elevations below 1000m. Historically, snowmelt accounted for roughly 15% of the runoff in these lower elevations; however, due to an increase in the fraction of rainfall, this contribution has decreased to less than 5%.

Conversely, at higher elevations above 4000m, we observed an increase in snowmelt runoff compared to historical values. These high-altitude areas tend to accumulate precipitation without immediate release as runoff throughout the year. Therefore, the presence of snowmelt runoff from these regions has increased, contributing to the overall water availability in the basin.

In terms of evaporation, we noticed a slight increase in lowland areas. This can be attributed to the changing climate conditions, including higher temperatures and potential changes in vegetation cover. However, the highland areas exhibited significantly higher values of evaporation. This is primarily due to the presence of glaciers, which act as a constant supply of water during the season, leading to increased evaporation rates in these regions.

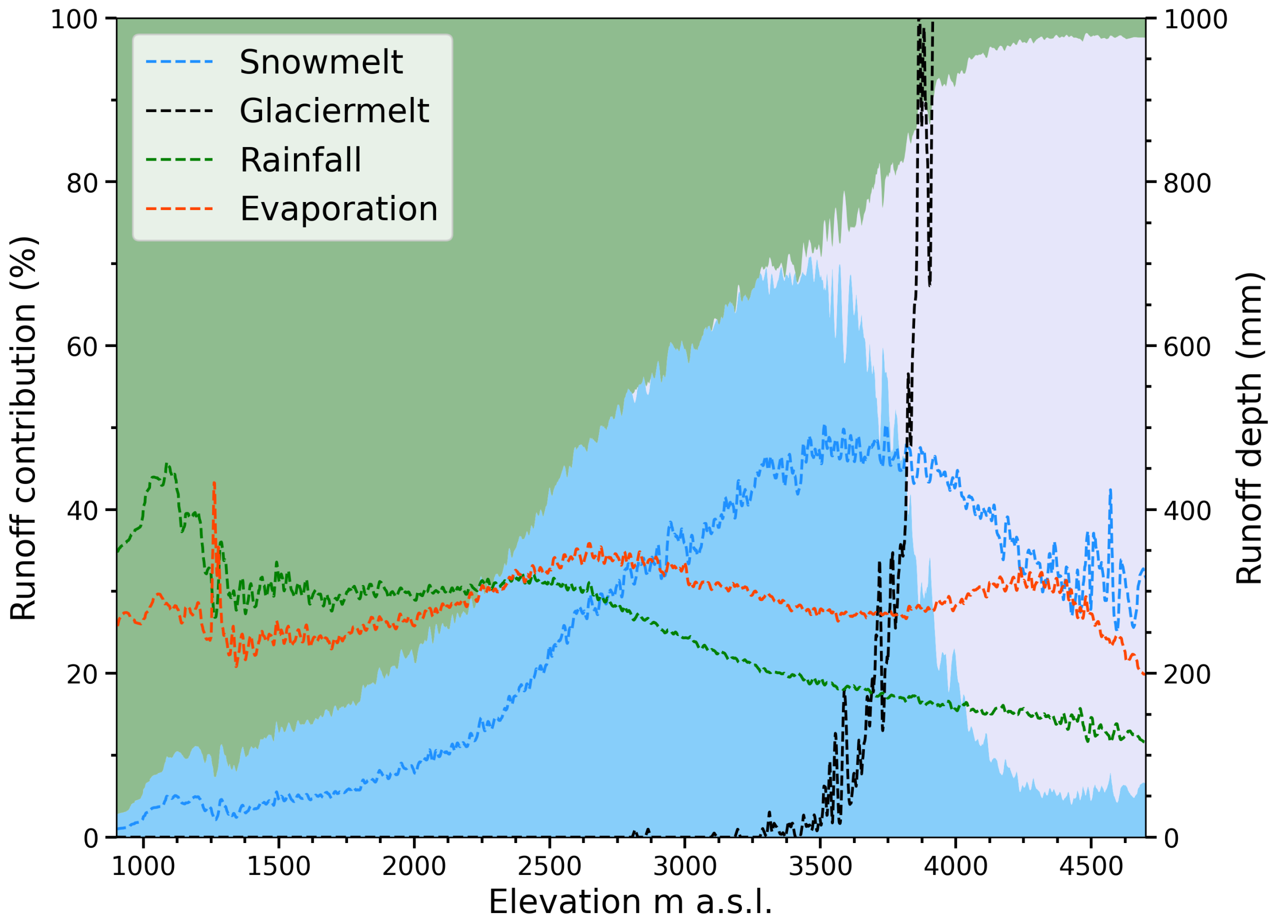

Figure 4.18 Runoff components along elevation in Naryn River Basin (projected).

The changes observed in the distribution of runoff and evaporation highlight the complex interactions between climate, elevation, and various water sources in the study area. The decrease in snowmelt runoff in lower elevations emphasizes the shift towards more rain-dominated precipitation patterns, which can have implications for water resource management and ecosystem dynamics.

The increase in snowmelt runoff at higher elevations indicates the importance of these areas as water storage reservoirs, gradually releasing water throughout the year. Understanding the dynamics of snow accumulation and melt in these high-altitude regions is crucial for accurately predicting water availability and managing water resources effectively.

Evaporation results in the projected climate for glacier areas, we observed an increase in evaporation rates. This can be primarily attributed to the increased supply of water from glaciers, which is mainly due to the unchanged area of the glaciers and the presence of snow. Additionally, the presence of snow in glacier areas further contributes to the increased water supply. Snow acts as a temporary reservoir, storing water until it melts and becomes available for evaporation. With the projected climate changes, including higher temperatures, the timing and duration of snowmelt may be affected, potentially resulting in a prolonged period of water availability for evaporation.

In conclusion, our analysis of the annual distribution of runoff results across elevations reveals significant changes in the generated runoff and evaporation patterns. The decrease in snowmelt runoff in lower elevations, coupled with the increase in snowmelt runoff at higher elevations, reflects the influence of changing precipitation patterns and the role of elevation in the water cycle. The rise in snowmelt runoff at elevated altitudes underscores the significance of these regions as natural water reservoirs, slowly discharging water over the course of the year. Gaining a comprehensive understanding of the snow accumulation and melting processes in these high-altitude areas is vital for precise predictions of water availability and effective water resource management. These findings underscore the importance of considering these factors in water resource management strategies and highlight the need for further research to understand the implications of these changes on water availability and ecosystem dynamics in the basin. In the future, it may be advisable to consider constructing additional water storage capacity in high altitude regions as a means to mitigate the effects of climate change and effectively manage seasonal water supply.

4.8 Discussion on Modeling Framework and Results

Indeed, the use of complex physical models in glacio-hydrological modeling offers several advantages over simpler degree-day models. These advantages stem from the ability of complex models to capture spatial variability by considering factors such as topography and shading, as well as the capacity to incorporate energy balance components and process interactions.

By accounting for topography and shading, complex models can better simulate the spatial distribution of melt processes across a glacier or glacierized basin. This is particularly important in mountainous regions where glaciers often exhibit significant spatial variability in terms of slope, aspect, and exposure to solar radiation. By considering these factors, complex models can provide a more accurate representation of the meltwater production and runoff processes.

Furthermore, complex models have the capability to integrate mass balance modeling of glaciers into hydrological models. This integration is crucial for accurately simulating streamflow and assessing water resources in glacierized catchments. By explicitly considering the mass balance of glaciers, complex models can account for changes in glacier volume and extent, which directly impact the hydrological regime.

However, it is important to note that there can be differences in temporal and spatial resolution among complex models, which can introduce additional variations in model outputs, even for the same type of model. Fully distributed glaciological models often run at grid resolutions ranging from 10 m to 250 m, with higher resolutions generally providing more accurate representations of the system. However, higher resolutions also require more computational resources and longer runtimes.

In our study, we opted for a resolution of 1 km for regional simulations due to constraints and data availability. While this lower resolution may introduce some errors and limitations in capturing spatial variability and finer-scale processes, it was a pragmatic decision to strike a balance between capturing detailed variations and ensuring sufficient data for accurate modeling. This resolution was found to be optimal for our research goals and allowed us to obtain meaningful insights into the hydrological dynamics of the glaciated basins in the inner Tien-Shan mountains.

Mass balance gradients are critical in assessing the performance of glaciological models as they provide valuable insights into the processes governing ice accumulation and ablation along the elevation profile of a glacier. These processes include snowfall, melting, and sublimation, which are influenced by variations in temperature, precipitation, and other climatic factors.

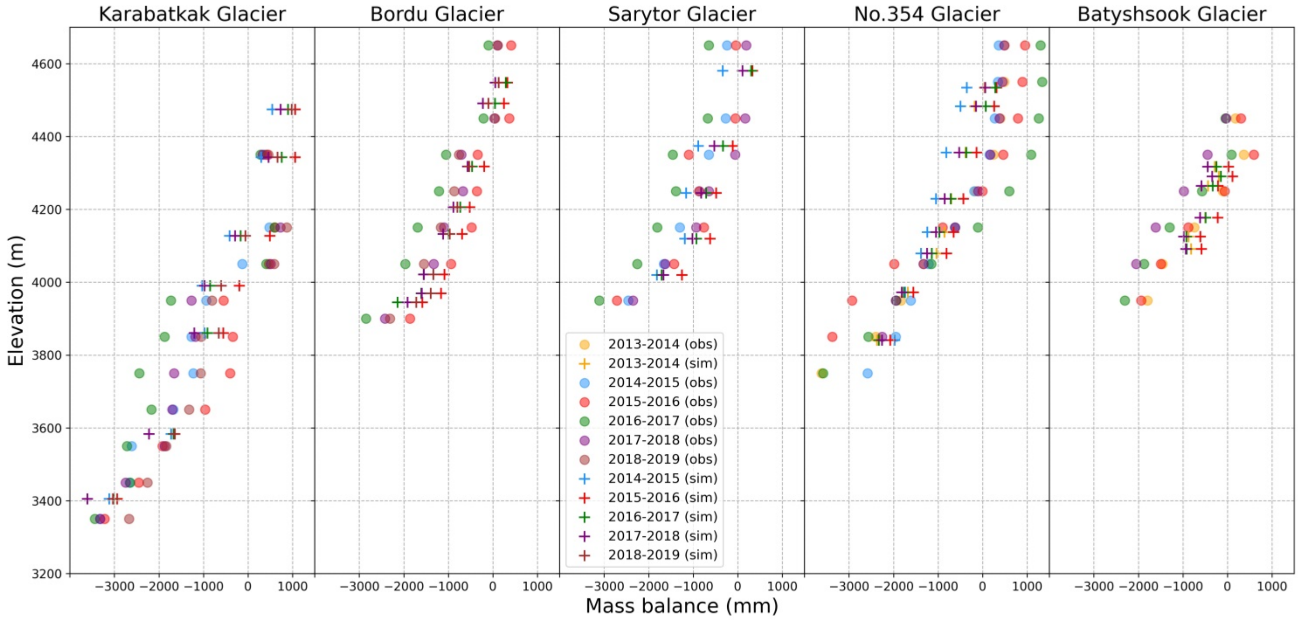

Figure 4.19: Observed and simulated mass balance profiles of observed glaciers (Figure 1b). Different colors are set for glaciological years.

We analyzed the modeled mass balance gradients (as shown in Figure 4.19) to examine the accuracy of the model in capturing the variations in mass balance along the elevation profile of small-scale glaciers. It is worth noting that the model resolution can introduce uncertainties in calculating the mass balance, particularly for small-scale glaciers. This is because the model may not fully cover the necessary elevation bins required to accurately represent the mass balance variations.

High-resolution glaciological simulations, which consider the representation of mass balance gradients, can offer more precise results, especially for small-scale glaciers. By capturing the fine-scale variations in mass balance along the elevation, these high-resolution simulations can improve the accuracy of modeling and enhance our understanding of the processes driving ice accumulation and ablation.

However, it is important to acknowledge that the lack of high-resolution input data, such as gradients of precipitation and temperature strongly related to elevation, contributes to the uncertainties in the modeled mass balance gradients. Precise representation of these gradients is crucial for accurately estimating the mass balance of glaciers. Insufficient data availability at high resolutions can limit the ability of models to capture the complex interactions between climatic variables and glacier response.

The results of the mass balance modeling provide estimates of the overall mass balance gradient for several glaciers in the study area. It is observed that the Sary-Tor Glacier has a mass balance gradient of 0.3 m w.e. yr-1 per 100 m, while Kara-Batkak has a gradient of

0.37 m w.e. yr-1 per 100 m, Bordu has a gradient of 0.34 m w.e. yr-1 per 100 m, Batysh-Sook has a gradient of 0.4 m w.e. yr-1 per 100 m, and Glacier No. 354 has a gradient of 0.31 m w.e. yr-1 per 100 m.

Comparing these findings with previous research in the study area, it is observed that the mass balance gradient for the adjacent Davydov Glacier was estimated as 0.3 m w.e. yr-1 per 100 m (Aizen and Zakharov, 1989). For Sary-Tor, a gradient of 0.4 m w.e. yr-1 per 100 m was reported (Ushnurtsev, 1991), and for Batysh-Sook, the gradient was found to be 0.45 m w.e. yr-1 per 100 m (Kenzhebaev et al., 2017). Other studies have reported different gradients, such as 0.5 m w.e. to 0.6 m w.e. yr-1 per 100 m in the reconstructed mass balance of glaciers in the study region (van Tricht et al., 2021), 0.68 m w.e. yr-1 per 100 m in the ablation zone of Glacier No. 354 (Kronenberg et al., 2016), and 0.6 m w.e. yr-1 per 100 m for the south-faced Grigoriev Glacier (Fujita et al., 2011).

Table 4.1: Comparison of mass balance gradients of modeled glaciers.

Glaciers	**Mass balance gradients (m w.e. yr^{-1} per 100 m)**		**References**
	This study	Other studies	
Kara-Batkak	0.37	0.5-0.6	van Tricht et al. (2021)
Bordu	0.34		
Sary-Tor	0.3	0.4	Ushnurtsev (1991)
No.354	0.31	0.68	Kronenberg et al. (2016)
Batysh-Sook	0.4	0.45	Kenzhebaev et al. (2017)

It is important to note that the modeled mass balance gradients may not fully capture the spatial variability of the glaciers or cover specific elevation bands due to limitations in temperature downscaling at a resolution of 1 km and the representation of precipitation in the dataset. These limitations can affect the accuracy of the modeled gradients and introduce uncertainties in estimating the mass balance variations.

Regional climate conditions and precipitation patterns play a significant role in influencing the accumulation component of glaciers. This is evident in the case of Bordu and Glacier No. 354, where significant differences in observed snow accumulation during the 2015-2017 seasons are observed. The snow accumulation at an elevation of 4650 m for Bordu ranged from 410 mm to -100 mm to 100 mm for consecutive years, while for Glacier No. 354, it ranged from 954 mm to 1300 mm to 484 mm for the corresponding years. It is important to consider that the variability in observed snow accumulation can be attributed to differences in the methods used for data collection, which can contribute to the observed differences between the two glaciers.

The study findings provide valuable insights into the varying magnitudes of glacier contribution in the three examined basins. It is evident that the extent of the glaciated area plays a significant role, but the precipitation pattern and amount also have a substantial influence on glacier contribution.

Previous research conducted on twenty-four catchments in the Tien-Shan Mountains, using the glacier-enhanced Soil and Water Assessment Tool (SWAT) model, established a strong correlation between the glaciated area of the catchment and ice melt contribution. On average, the glacier contribution was found to be 10.5% (Zhang et al., 2016). Within a small catchment that encompasses the Kara-Batkak glacier, the modeling results estimated a glacier melt contribution of 47% during the glacier melting season. This highlights the significant impact that glaciers have on the overall water flow in the region. Long-term studies on runoff sources in the region, conducted by Dikikh and Mikhailova (1976), reported an average glacier contribution of 50% to total runoff. These findings align with the analysis of recent hydrometeorological data conducted by Satylkanov (2018), further emphasizing the crucial role of glaciers in contributing to the water flow.

Catchments with lower degrees of glaciation exhibit considerably lower ice melt runoff contributions, which consequently affects the overall runoff in those areas. This is illustrated in Figure 4.7b, where catchments with less glacier coverage show lower contributions from ice melt. Higher elevations with greater glacier coverage yield higher runoff volumes, and as the glaciers melt, significant changes in runoff variability can occur. This highlights the vulnerability of these regions to the effects of climate change and emphasizes the importance of understanding glacier contribution in water resource management.

However, accurately simulating glacier runoff and estimating its contribution to overall water flow requires considering various factors and potential sources of uncertainty. One crucial factor is the inclusion of shortwave radiation correction in the modeling process. For example, within the Kara-Batkak glacier tongue, average melting rates were found to be overestimated by 30% when radiation correction was not applied. This underscores the significance of accounting for topographic effects and incorporating accurate radiation data to reduce uncertainties and improve the accuracy of glacier contribution estimations.

In our study, we aimed to investigate and compare the performance of both temperature-index and energy balance models for simulating glacier melt. Additionally, we utilized the SiBUC model for non-glaciated areas to analyze runoff in the study region. The objective was to gain insights into the processes occurring in both glaciated and non-glaciated systems. As mentioned previously, more complex energy balance models have the potential to outperform temperature-index models by providing a more comprehensive understanding of the intricate processes taking place in glaciated systems. However, it is important to note that such modeling frameworks require enhanced accuracy in the preparation of meteorological forcing data, with a particular emphasis on radiation.

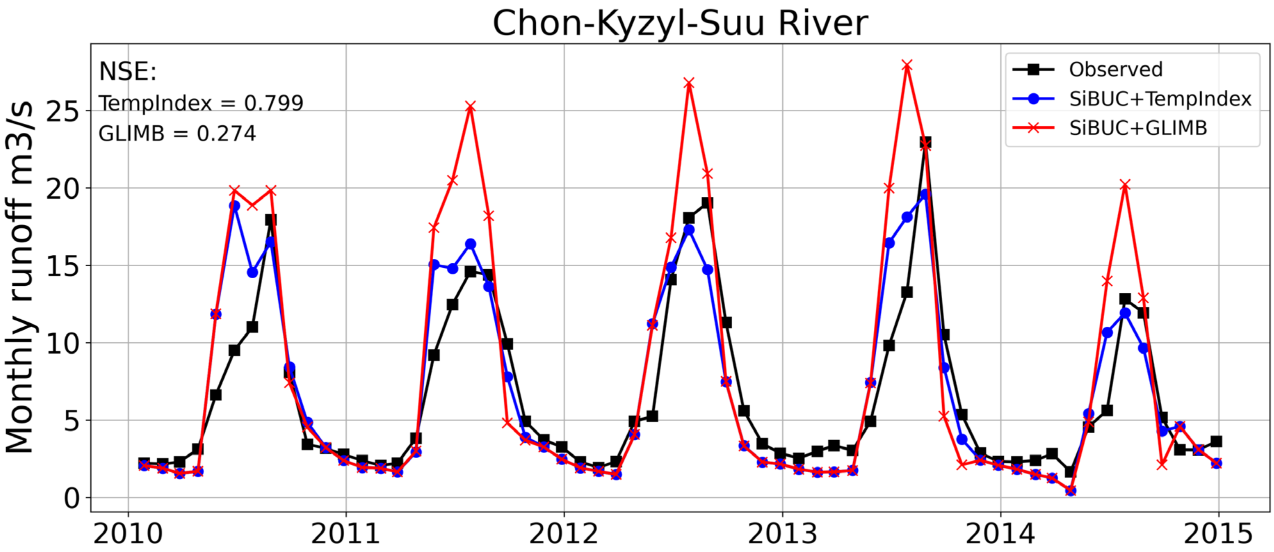

Figure 4.20 Comparison of simulation approaches without radiation correction.

During our comparisons, we evaluated the performance of the temperature-index model and the GLIMB model using raw data, meaning that the radiation data was not corrected or adjusted beforehand. The results revealed a clear overestimation of runoff during the summer period when utilizing the GLIMB model, as depicted in the Figure 4.20. Extensive warm period discharge can be attributed to overestimation of incoming solar radiation.

The findings highlight the significance of accurately accounting for radiation data when using energy balance models. Any inaccuracies or biases in the estimation of incoming solar radiation can lead to substantial discrepancies in the runoff estimations. Therefore, it is crucial to refine the methods used for collecting and processing radiation data to enhance the accuracy of the modeling framework. The overestimation of runoff during the summer period by the GLIMB model suggests that there may be other influential factors or processes that are not adequately captured or accounted for in the model. Further research and analysis are required to identify and incorporate these additional factors into the modeling framework to improve its performance and reliability.

In addition to the discussed factors, the uncertainties associated with subsurface flow in high mountain areas, such as the Tien-Shan, underscore the need for further research and exploration to enhance our understanding of these complex processes. The observed overestimation of fall season flows in the Kichi-Kyzyl-Suu catchment, as depicted in Figure 4.2b, could be attributed to variations in subsurface flow patterns compared to other basins.

Somers and McKenzie (2020) have described the key characteristics that distinguish groundwater processes in mountainous regions from those in areas with lower relief. The presence of high surface topography in mountainous areas results in deeper groundwater circulation, which in turn affects the dominant local flow paths and flow rates (Forster and Smith, 1988). These unique characteristics of mountain hydrogeology necessitate a deeper understanding of subsurface flow dynamics to accurately describe the water cycle in mountain systems.

However, the nature of these subsurface processes, particularly in the Tien-Shan region, remains largely unexplored, which limits our ability to precisely characterize and model the water cycle. The hydrogeological parameters of the subsurface are intricate, especially considering the influence of glacial deposition processes, which can significantly distort the results of regional-scale modeling.

To improve our understanding of subsurface flow in high mountain areas, further research should focus on investigating the complex interactions between surface and subsurface water resources. This could involve field surveys, geophysical investigations, and the collection of comprehensive hydrogeological data. By integrating these findings into hydrological models, we can enhance the accuracy of predictions and simulations of water availability and flow dynamics in mountainous regions.

Additionally, studying the influence of glacial deposition processes on subsurface flow patterns is crucial for capturing the full complexity of the water cycle in glaciated mountain systems. This could involve assessing the impacts of glacial retreat and changes in glacier coverage on groundwater recharge and discharge, as well as investigating the potential storage and release mechanisms within glacial and proglacial environments.

In conclusion, the uncertainties associated with subsurface flow in high mountain areas, including the Tien-Shan, emphasize the need for further research and exploration to advance our understanding of these intricate processes. The distinct characteristics of mountain hydrogeology, influenced by high surface topography and glacial deposition processes, require comprehensive investigations to accurately model the water cycle in these regions. By addressing these knowledge gaps, we can improve our ability to manage water resources in mountainous areas and mitigate the potential impacts of climate change on water availability.

Chapter 5: Conclusion

5.1 Summary of Findings

The study aimed to understand the hydrological dynamics and factors influencing runoff in glaciated basins within the inner Tien-Shan mountains of Kyrgyzstan. By utilizing integrated land surface, glacier energy-mass balance, and river routing models, the research quantified the contributions from various runoff sources and examined the influence of radiation data on glacier melt estimation.

The results revealed that the peak contribution of glacier melt occurred in July and August, with some basins reaching up to 54%. On an annual basis, glaciers contributed an average of 19% to the total runoff, while snowmelt and rainfall accounted for 58% and 23%, respectively.

Comparisons with previous studies in the Tien-Shan Mountains demonstrated consistency in the importance of glacial runoff. In the Northern Tien-Shan, glacier runoff ranged from 18-28% of the river flow, peaking at 40-70% during summertime. Additionally, the contribution of glacier meltwater to the total runoff in Central and Northern Tien-Shan was estimated as 42% and 36%, respectively.

Our findings revealed significant variability in the distribution of runoff components in these basins. Glacial runoff was primarily influenced by the percentage of glaciation in the basin, highlighting the importance of glacier coverage in determining the contribution of glacial meltwater to the overall runoff. On the other hand, rainfall runoff and snowmelt runoff were found to be influenced by various factors related to climatic conditions in the region and the topography of the basin. One key factor that influenced the average snowmelt component was the partitioning of precipitation into rain and snow. This partitioning played a crucial role in determining the amount of snowmelt runoff. Understanding this process is essential for accurate estimation of water resources and hydrological modeling in mountainous regions.

Furthermore, our study highlighted the significant role of topography in modeling melting processes throughout the year. The seasonal variability of glacier melt was found to be influenced by the local topographic characteristics of the basin. In case of Karabatkak glacier, incorporation of downscaled radiation data reduced overestimation of melting rate by 30%. This underscores the importance of considering the specific topographic features of a region when modeling melting processes and predicting runoff dynamics.

Another significant finding of our study was the sensitivity of incoming solar radiation to cloud cover. Cloud cover affects the amount of solar radiation reaching the Earth's surface, which in turn influences ice and snow melt processes. We employed a simple parameterization approach based on reanalysis data that took into account cloud transmissivity. This approach proved to be effective in improving the accuracy of ice and snow melt modeling. It can be applied to other regions with similar characteristics to enhance the reliability of hydrological simulations.

The Naryn River Basin in Central Asia is experiencing significant climate change impacts, particularly in its snow dynamics. Rising temperatures are leading to a reduction in snow accumulation and duration of snow cover, which has profound implications for the hydrological cycle. Regional climate models, such as the Nonhydrostatic Regional Climate Model (NHRCM), provide valuable insights into precipitation patterns in high mountain areas. The NHRCM dataset improves the accuracy of simulations and enhances our understanding of the potential consequences of climate change on water resources, ecosystems, and communities reliant on glaciated regions. However, challenges and uncertainties still exist in regional climate modeling, emphasizing the need for cautious interpretation of findings. The study highlights the crucial role of snow and glacier melt in the basin's water balance, with decreased snow accumulation posing challenges for water resources, agriculture, and ecosystems. Proactive measures, such as water management strategies and conservation practices, are necessary to mitigate potential water scarcity risks. Understanding the mass balance of glaciers is vital for assessing their health and behavior and quantifying their contributions to water resources. Positive mass balance indicates a healthy and growing glacier, while negative mass balance leads to glacier shrinkage and reduced water availability downstream. The consequences of climate change in the Naryn River Basin underscore the urgent need for action and informed decision-making to address these impacts.

The findings emphasized the utility of the integrated modeling approach in understanding hydrological processes and quantifying runoff components in data-scarce high mountain regions. The study showcased the potential of physically-based models in capturing the underlying physical processes and improving projections for future scenarios.

5.2 Contributions to Knowledge

The contribution of this study lies in its application of integrated land surface, glacier energy-mass balance, and river routing models to determine the hydrological contributions from various runoff sources in glaciated basins within the inner Tien-Shan mountains of Kyrgyzstan. The study addresses the need for accurately quantifying runoff sources and hydrological processes in glaciated mountain basins, which is crucial for water resource management under climate change.

Existing studies have predominantly used temperature-index models for glacio-hydrological studies, with only a small percentage using the energy-balance approach. The widespread use of temperature-index models is due to their practicality and accessibility, as they require minimal input data, such as air temperature. However, these models may not fully capture the complex physical processes occurring in high mountainous areas.

In contrast, this study utilizes a cutting-edge land surface model integrated with a glaciological model, which is based on fundamental physical principles such as conservation of mass and energy. This approach allows for a more robust and accurate representation of the modeled system, leading to a better understanding of the underlying physical processes and improved projections for future scenarios.

Furthermore, the study incorporates gridded reanalysis meteorological forcing data, which are validated using observational data, to accurately represent the high mountain conditions. The data preprocessing stage includes topographic downscaling of incoming solar radiation, considering factors such as slope, aspect, shading by surrounding topography, and cloudiness. This comprehensive analysis enables the assessment of the impact of these factors on ice and snow melt processes.

The uniqueness of the methodology used in this study lies in the integration of radiation data and glaciological models in physically based hydrological modeling. By addressing the challenges of downscaled radiation data and its influence on glacier melt estimation and overall runoff, the study enhances the accuracy and reliability of hydrological models in glacier-dominated watersheds.

Overall, this study contributes to the field of hydrological modeling by providing insights into the hydrological dynamics in glaciated basins and the role of various factors in influencing runoff. The comparison of model results with observed data validates the performance of the integrated model and helps in understanding the accuracy and reliability of the modeling framework. The study's findings are significant for water resource planning and management in data-scarce high mountain regions, particularly in the context of climate change.

5.3 Implications for Water Resource Management

Hydrological modeling is essential for understanding the implications of runoff source determination, particularly in the context of glacier runoff, for water resource management.

Glacier runoff significantly impacts catchment hydrology by temporarily storing and releasing water on various time scales (Gao et al., 2010). However, it is important to note that glacier runoff is just one component of the total runoff, and it interacts with various other factors such as precipitation, evaporation, and exchange with subsurface flow regimes and groundwater (Kaser et al., 2010). Therefore, accurately determining the contribution of glacier runoff to the total basin runoff is vital for assessing the effects of glacier change on regional water resources (Liu et al., 2021).

Hydrological modeling has become an indispensable research approach for water resources management in large glacierized river basins (Chen et al., 2017). It allows for the estimation of daily and monthly runoff characteristics, assessment of other variables of interest, and modeling the combined impact of climate change and other drivers on hydrological states and fluxes (Chiew et al., 2009). The modeling of glacial discharge, however, has been identified as an area that requires more focus and attention (Chen et al., 2017).

Glaciers and snow play a crucial role in regulating the instability of runoff caused by variability in precipitation in mountain basins (Deng et al., 2019). The regulation of glaciers on runoff becomes stronger with an increase in glacier coverage (Wang et al., 2017). Furthermore, the contribution of each runoff component, including rainfall, snowmelt, and glacier runoff, to the total runoff can be studied using well-established hydrological models (Su et al., 2022).

Understanding the implications of runoff source determination by hydrological modeling, including glacier runoff, is essential for sustainable water resource management. It involves assessing the proportion of glacier runoff to total basin runoff, determining the magnitude of the effects of glacier change on regional water resources, and modeling the combined impact of climate change and other drivers on hydrological states and fluxes. Therefore, accurate hydrological modeling that incorporates glacier runoff is crucial for effective water resource management, especially in glacierized river basins.

5.4 Limitations of the Study

While this study makes valuable contributions to the understanding of hydrological processes in the Tien-Shan Mountains and the Issyk-Kul Basin, it is important to acknowledge its limitations. The study relies on available data sources, including gridded reanalysis meteorological forcing data and observational data. These data sources may have inherent uncertainties or limitations in terms of accuracy and spatial/temporal resolution. The use of such data may introduce uncertainties in the model simulations and results.

Although the study utilizes integrated land surface, glacier energy-mass balance, and river routing models, the representation of certain processes may still be simplified. For example, the models may not fully capture the complexities of glacier dynamics or the intricate interactions between different components of the hydrological system. These simplifications could potentially lead to discrepancies between model outputs and the actual system behavior. For instance, assumptions about the spatial distribution of radiation and the parameterization of physical processes in the models may have an impact on the estimated runoff components.

The study focuses on the inner Tien-Shan mountains of Kyrgyzstan and may not fully represent the hydrological processes in other parts of the Tien-Shan Mountains or the entire Issyk-Kul Basin. The study evaluates the model simulations against observational data, but it is important to consider the limitations of the available observational data. The scarcity of long-term, high-quality observational data in remote and high-altitude regions may introduce uncertainties in the validation process.

Despite these limitations, this study serves as a valuable starting point for understanding hydrological processes and quantifying runoff components in the Tien-Shan Mountains and the Issyk-Kul Basin. Further research and improvements in data availability, model complexity, and validation techniques can help address these limitations and enhance our understanding of the hydrological dynamics in these regions.

5.5 Recommendations for Future Research

Based on the findings and implications of this study on hydrological processes and runoff components in glaciated basins of the inner Tien-Shan mountains in Kyrgyzstan, several recommendations for future research can be made. These recommendations aim to address the limitations and gaps identified in the current study and further advance our understanding of water resource management and climate change impacts in high mountain regions.

Firstly, future research should focus on expanding the spatial and temporal coverage of observations. The study area in this research is limited to specific catchments within the inner Tien-Shan mountains. To gain a more comprehensive understanding of hydrological processes, it is essential to include a broader range of basins and glaciers in the analysis. Additionally, extending the observation period will provide valuable insights into seasonal and long-term variations in runoff components and their response to climate change.

Secondly, there is a need for more detailed and accurate meteorological data. The study utilized gridded reanalysis meteorological forcing data, which may have limitations in representing local topographic influences on solar radiation and cloud transmissivity. Future research should prioritize the collection of high-resolution meteorological data, including variables such as solar radiation, cloud cover, wind speed, and temperature, to improve the accuracy of hydrological models.

Furthermore, incorporating remote sensing techniques and satellite data can enhance the understanding of glacier dynamics and their contribution to runoff. Remote sensing can provide valuable information on glacier extent, mass balance, and surface characteristics, allowing for a more comprehensive assessment of the role of glaciers in hydrological processes. Future research should explore the integration of remote sensing data with hydrological models to improve the accuracy of glacier melt estimations and overall runoff predictions.

Additionally, to further improve the accuracy of modeling glacier-associated processes, it is recommended to explore the use of finer scale glaciological models coupled with hydrological models at a regional scale. This integration allows for a more detailed representation of the complex dynamics occurring within glaciers and their interaction with the broader hydrological system. Fine scale glaciological models, such as ice flow models or energy-balance models, provide a more comprehensive understanding of the internal processes of glaciers, including ice flow, mass balance, and surface energy exchanges. By coupling these models with hydrological models, which simulate the movement of water through the catchment, it becomes possible to capture the intricate feedback mechanisms between glacier dynamics and runoff generation.

It is crucial to consider the potential impacts of future climate change scenarios on hydrological processes in high mountain regions. This study focused on current climatic conditions, but projecting future changes in temperature, precipitation patterns, and glacier dynamics is essential for effective water resource management. Future research should incorporate climate models and scenario analysis to assess the potential changes in runoff components under different climate change scenarios.

Furthermore, there is a need for more comprehensive field observations to validate and improve the performance of hydrological models. Collecting data on discharge, glacier mass balance, and snow water equivalent will allow for a more robust evaluation of model simulations. This information can be used to calibrate and validate the integrated models, enhancing their reliability and applicability in data-scarce high mountain regions.

Lastly, considering the socio-economic aspects of water resource management is vital. Future research should explore the socio-economic implications of changing hydrological processes in high mountain regions, particularly in arid areas like Central Asia.

Understanding the potential economic, political, and social consequences of altered water availability and seasonality can inform policy-making and adaptation strategies.

In conclusion, future research should expand the spatial and temporal coverage of observations, improve meteorological data quality, integrate remote sensing techniques, consider climate change scenarios, enhance field observations for model validation, and address socio-economic aspects. By addressing these recommendations, researchers can advance our understanding of hydrological processes and runoff components in high mountain regions, contributing to effective water resource management and climate change adaptation strategies.

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