Climate Change Scenarios

for Glaciers and Meltwater Contribution on Water Availability in Central Asia

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Changes in glacier meltwater contribution from the Tien Shan and Pamir until the end of the 21st century

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CHAPTER 1: Introduction

The cryosphere in Central Asia is a vital freshwater resource and a key indicator of climate change. However, understanding their historical and future impacts on the region's water balance is still limited (Grigori et al., 2006). The response of the cryosphere to climate change is affecting the cryosphere in various ways, leading to different meltwater contributions across the catchments, which significantly impact water availability for mountain communities and cascade downstream (Varis, 2014; Xenarious et al., 2019; Immerzeel et al., 2020; Nusser, 2017; Nusser et al., 2019). This in turn affects water availability for local mountain communities, which are already vulnerable to fluctuations in supply and climate-related hazards (Fay & Patel, 2008). Growing populations and water demand, increasing water stress (Pohl et al., 2017), further challenge the adaptive capacity of rural communities (Garcia & Brown, 2009; Nusser et al., 2019), which often have limited financial and institutional resources available (Manandhar et al., 2017).

Predictions of increased runoff and declining ice volumes underscore the urgent need for effective water management strategies. The warming trends observed in the Tien Shan Mountains since the 1970's (Aizen et al., 1995; Marchenko et al., 2007; Forsythe et al., 2017) further demonstrate the importance of adaptive measures to address changing hydrological patterns. The complex dynamics of the cryosphere require a comprehensive approach to water resource management in Central Asia. Continued efforts of monitoring and investment in process understanding are crucial for adapting to changing hydrological conditions and mitigating the impacts of climate change. Given the diverse water needs and challenges faced by Central Asian countries, a collaborative approach to improved future prediction is essential. Effective cryosphere monitoring should build on existing frameworks such as the Global Terrestrial Network for Glaciers (GTN-G) and the Global Terrestrial Network for Permafrost (GTN-P) and form the base for improved future scenarios. In turn, adaptation and mitigation strategies must be tailored to the specific needs of each region, country, and watershed. Recognizing the heterogeneity of water-related challenges in each country, transboundary cooperation should focus on targeted initiatives to address these specific issues.

For example, Kazakhstan, with its large lakes and rivers, struggles with uneven water distribution and external dependencies (Karatayev et al., 2017). Kyrgyzstan relies heavily on cryospheric resources for irrigation (Hill et al., 2017; Saks et al., 2022; FAO, 2016), while Uzbekistan uses nearly 90% of the total water use for irrigation from snow and glacier melt in the Pamir and Tien Shan mountains (Zhumaeva, 2021). Turkmenistan faces increasing water scarcity due to climate change and relies heavily on the Amu Darya (Zonn, 2012). Tajikistan, a major contributor to the Amu Darya, depends primarily on its extensive cryosphere for water resources (Dukhovny et al., 2014). These country specific challenges will only increase in the future. Improving the understanding of the country's specific needs for improved water resource management, based on better scientific knowledge of expected changes in key water resources under ongoing and future climate change, will be of primary importance.

The Tien Shan and Pamir are uniquely situated with heterogeneous climatic environments, towering mountain ranges, and extensive cryospheric systems, including seasonal snow cover, glaciers and permafrost. The complex interactions between these elements have a significant impact on the region's water availability and create diverse hydrological regimes influenced by snowmelt, glacial melt and groundwater. Aizen et al. (1995) classified the rivers of the Tien Shan into four types based on their hydrographic regimes, characterized by different runoff formation processes: those fed by snowmelt, glacial melt, rainfall and groundwater, each with unique discharge characteristics.

Numerical models are commonly used to reconstruct past development and predict the future response of the different hydrological regimes. Simple models are suitable for better understanding the regional response of the cryosphere and the general patterns and changes in meltwater discharge under different hydrological regimes (Lutz et al., 2014; Immerzeel et al., 2015).

The main limitation of such computationally efficient models is the inability to simulate small-scale processes using inferred empirical or statistical relationships with fixed parameters (Rounce et al., 2014). Region-wide model applications often neglect relevant processes (e.g. sublimation, snow thermal insulation, soil porosity, refreezing of meltwater), which can have a significant impact on the representation of snow, firn and ice evolution over time (Kronenberg et al., 2021). Especially for non-linear and poorly understood feedbacks, future predictions can be very uncertain. More detailed and complex models are useful to understand and quantify the role of individual processes linking the atmosphere, cryosphere and hydrosphere (e.g. Mölg et al., 2014). Such physically based models can better represent the chain of processes under climate change that affect the cryosphere and its meltwater release response, including in non-linear ways. However, they are often too computationally intensive, include a large number of calibration parameters which are poorly constrained, require large amounts of input data that are often unavailable for data-sparse regions, and thus their application remains limited to single sites or points. Thus, we often have to compromise between efficient, regionally applicable models that greatly simplify physical processes and focus on impact studies, or physically based models that have a complex and more accurate representation of processes but are only applicable at single sites or even points. Combining both approaches is a key to capture the large-scale impacts of climate change-induced cryospheric changes and to improve our understanding of the future cryosphere change impact. In this report, we focus on glacier changes and their impacts on freshwater resources for the different Central Asian basins until the end of the century. We use the results of a strongly parameterized glacier evolution model. In the discussion, we relate the impact-oriented modelling results to more detailed process-oriented studies. In the next step, we use improved climate time series to predict changes in snow cover and snowmelt and hydrological models that incorporate glaciological and snow cover observations to better predict the future influence of the cryosphere on water availability for Central Asia.

1.1 Current stage of the cryosphere and it's role as major water resource in Central Asia

The cryosphere plays a critical role in shaping the hydrological regime of the region. As Central Asia faces the pressing challenges of climate change, a comprehensive understanding of its impacts on the cryosphere - and proactive adaptation and mitigation of these impacts - will be critical for sustainable water resource management and strengthening regional resilience.

Seasonal snow cover constitutes a major component of the annual water budget in Central Asia, contributing over 74% to the water availability in the Syr Darya and over 69% for Amu Darya (Armstrong et al., 2019). In comparison, rainfall accounts for only 23% , and glacier ice contributes 2 and 8% to annual runoff, respectively (Armstrong et al., 2019).

During the dry season from July to September, glacier melt becomes crucial. The contribution of glacier meltwater can increase dramatically during the growing season, rising to between 70% and 90% (Huss & Hock, 2018; Saks et al., 2021). The response of glaciers in Central Asia is heterogeneous both in space and time, leading to heterogeneous changes in meltwater contributions from one catchment to another, which complicates water availability for mountain communities and the downstream water users. This variability, combined with changing future glacier melt regimes and extreme weather events, poses significant challenges for water resource management.

Beyond glaciers, the Central Asian region is home to the largest area of mountain permafrost globally. This area encompasses approximately 3.5 million km^2, representing about 15% of the total permafrost extent in the northern hemisphere (Gruber 2012). Changes in the thermal regime of permafrost can significantly affect local hydrology, land surface energy and moisture balances, land-atmosphere carbon exchange, ecosystems, and engineering infrastructure (Jin et al., 2021; Hjort et al., 2022).

Kazakhstan: Climate change has altered patterns of solid precipitation, with studies showing varied effects across Kazakhstan. For example, while some areas like Altai and Tien Shan have experienced decreased snow cover duration and depth (Zhou et al., 2017), other studies indicate increased snow thickness in the Tien Shan from 1961 to 2014 (Li et al., 2019). Recent observations from the Kazakh Hydrometeorological Service reveal a 72% increase in snow depth and snow water equivalent (SWE) in the Altai Mountains over the last 30 years (Pimankina & Takibayev, 2021). In Kazakhstan, ground observations and remote sensing have shown that mountain glaciation has decreased by approximately 43% in area and 65% in volume over the past 65 years (Severskiy et al., 2016; Kapitsa et al., 2020; Kokarev et al., 2022; Gorbunov et al., 2018)). Currently, the Central Tuyuksu Glacier in the Kishi Almaty River basin is the only glacier in Kazakhstan with continuous mass balance measurements, which have been conducted since 1957 (WGMS, 2020). The glacier has shown a predominantly negative mass balance (-0.42 m w.e. yr^{-1}) over the observation period from 1958 to 2022 (Kapitsa et al., 2020; WGMS, 2023). For the Tien Shan and Pamir regions, Barandun et al. (2021) reported an area-weighted mean mass balance of -0.23 ±0.37 m w.e. yr^{-1} from 1999/00 to 2017/18. Permafrost temperature observations at three sites between 1974 and 1977 and again from 1990 to 2009 indicate warming in the Kazakh part of the Tien Shan mountains over the past 35 years, with temperature increases ranging from 0.38°C to 0.68°C at depths of 14 to 25m (Marchenko et al., 2007; Lin et al., 2010; Severskiy, 2017). Warming trends in permafrost and air temperatures indicate that permafrost may reach near-zero temperatures within the next 20 to 30 years.

Kyrgyzstan: The region's water resources heavily depend on snow, glaciers, and permafrost playing a critical role in providing water during dry summers. Aizen et al (1997) analyzed snow data from 110 stations for the period from 1940 to 1991 and found a decrease of mean annual snow depth of 8 - 14 cm at elevations below 2000 m a.s.l. and of 6 - 19 cm at higher elevations. Long-term mass balance data, crucial for assessing glacier health, reveal a negative trend in glacier mass, with various studies indicating annual losses ranging from -0.16 to -0.61 m w.e. yr^{-1} (Hoelzle et al., 2019; Barandun et al., 2018; Barandun et al., 2015; Hoelzle et al., 2017; Kenzhebayev et al., 2017; Kronenberg et al., 2016; Azisov et al., 2022). Despite some years showing a positive balance due to short-term (or temporarily) favourable conditions, the overall trend across multiple monitored glaciers points to increased ablation outpacing accumulation. Temperature measurements in two permafrost boreholes to a depth of 30 m indicate a warming of around 1°C from 1986 to 2024. New geophysical observations in Kyrgyzstan show an estimate of different ice contents for different landforms and will allow larger estimates of the frozen ice contents in the high mountain environments.

Tajikistan: glaciers cover 8,400 km², accounting for 6% of the country surface. The Fedchenko Glacier, one of the largest outside the polar regions (Lambrecht et al., 2014), has significantly thinned since 1928, with accelerated thinning rates since 2000 (Lambrecht et al., 2018). The estimated glacier-wide mass balance is negative, with a decline of -0.27 m w.e. yr^{-1} from 2000 to 2011 and -0.51 m w.e. yr^{-1} from 2011 to 2016 (Lambrecht et al., 2018). Tajikistan's cryosphere is responding heterogeneously to climate change, complicating the understanding of water availability and its future changes. The lack of direct observations hampers insights into local processes, emphasizing the need for enhanced monitoring and modeling to address rising water demand. Direct (in-situ) observations or data on permafrost in Tajikistan are scarce, and existing permafrost distribution maps are often based on simplified models that overlook key factors influencing permafrost occurrences (e.g. Gruber & Mergili, 2013; S. Gruber, 2012). In the Pamir, Mergili et al. (2012) identified about 84% of Gorno-Badakshan Autonomous Oblast as potential permafrost, covering approximately 54 000 km^2. Gorbunov (1978) suggested sporadic permafrost in the Pamir Alay starts at 3400 - 3800 m a.s.l., with continuous permafrost above 4000 m a.s.l. Nevertheless, permafrost research and monitoring in Tajikistan is only now in its initial stage, therefore much more efforts are needed to reach a good understanding of permafrost distribution and ice content.

Uzbekistan: Recent studies indicate a decline in snow cover for Uzbekistan, supported by satellite data analyses showing reduced snow extent and duration over the past decades. Historical precipitation trends also suggest a slight decrease, leading to expectations of reduced snow cover, especially in lower-elevation watersheds (TNC Uzbekistan, 2016). Glaciers in Uzbekistan, primarily located in the Kashkadarya, Pskem, and Surkhandarya basins, have shrunk significantly. Between 1957 and 2010, glacier area decreased by 14.4% to 56.7%, with many smaller glaciers forming as larger glaciers disintegrate (Kudyshkin et al., 2014). Remote sensing-based measurements indicate substantial reductions in ice volume across these basins. Current research includes ongoing monitoring of the Barkrak Middle Glacier, the only continuously observed glacier in Uzbekistan, which has shown an accelerating trend in mass loss (Hoelzle et al., 2017; CICADA project, University of Fribourg & ALM-202107010).

The heterogeneous response of the cryosphere in Central Asia will require continuous monitoring to assess its impact on future water resources in Central Asia, and therefore how climate change will affect water management in each country. It is vital to prioritize ongoing research and monitoring to refine predictions and address uncertainties concerning cryospheric components. Collaborative international efforts will be key in developing comprehensive strategies to safeguard water resources, ecosystems, and communities throughout Central Asia.

1.2 Climate change in Central Asia and it’s effect on the cryosphere

Central Asia, comprising Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, is characterized by arid to semi-arid climates with significant temperature extremes and complex topography. Altitudes range from below 150m a.s.l. to over 7000m a.s.l. in the Tien Shan and Pamir ranges (Chub, 2007). Average temperatures vary widely, with January minima as low as -54°C in Kazakhstan and July maxima as high as 50 °C in the Kyzylkum Desert. Annual precipitation also varies, where the plains receive around 250mm, the foothills 250-500 mm, and some mountain areas up to 2000 mm (Chub, 2007). Approximately 80 million people depend on water from the region. Over 25,000 glaciers contribute significantly to the flow of the Amu Darya and Syr Darya rivers and serve as indicators of climate change (Barandun et al., 2020; Kriegel et al., 2013). Studies using Global Climate Models (GCMs) indicate a significant trend of atmospheric warming in Central Asia (3 °C to 11.4 °C by 2100) and a decrease in precipitation, particularly in the southeastern part of the region (Ozturk et al., 2012; Ozturk et al., 2017). Downscaled climate scenarios suggest temperature increases of up to 7°C in northern areas of Central Asia and changing precipitation patterns, with wetter winters in the north and drier summers overall (Mannig et al., 2013; Huang et al., 2014). Research has also examined the role of atmospheric circulation in precipitation extremes under global warming. Zhao et al. (2018) found that the subtropical westerly jet could shift southward, potentially increasing summer precipitation in northern regions but introducing uncertainty elsewhere. Meanwhile, Reyers et al. (2013) projected a decrease in annual precipitation in the Aksu River basin. The negative impacts of global warming on glaciers have raised concerns about water availability, with projections of significant shrinkage affecting the Tien Shan and Pamir regions (Sorg et al., 2015; Kure et al., 2013). However, predictions of future glacier changes remain highly uncertain for the region.

In summary, Central Asia faces severe consequences from climate change, including glacier retreat, water scarcity, and desertification, with implications for society and ecosystems. Addressing these challenges requires improved water management, sustainable regional collaboration, and effective climate risk management strategies.

1.3 Water Resources in Central Asia

Fig. 1.1.1: Schematic view of surface water resources and withdrawal in Central Asia (Credits: Zoi Environment Network, 2010)

Central Asia relies heavily on freshwater resources for socioeconomic development, with countries interconnected by transboundary water resources (Abdullaev et al., 2019). Approximately 6,000 rivers originate in mountainous regions, primarily fed by snow and glacier melt, particularly from the Pamir, Hindu Kush, and Tien Shan ranges (Dukhovny et al., 2014; Djumaboev et al., 2019; Armstrong et al., 2019). The Amu Darya and Syr Darya are the region's major rivers, contributing significantly to the Aral Sea basin (Table 1.3.1), but their inflow to the Aral Sea has decreased by about 90% due to increasing water demand and climate change (Safronova, 2009; Djumaboev et al., 2019). Tajikistan and Kyrgyzstan are the primary contributors to these rivers, relying heavily on glacial melt and snowpack (Saks et al., 2022; Aizen et al., 1995). While snow and glacier melt are well-studied, the role of permafrost as a water resource remains underexplored. Water resources in Kazakhstan are dominated by surface water, with significant dependence on external supplies (Karatayev et al., 2017a). Agriculture consumes about 75% of water resources (Dostai, 2012; Medeu et al., 2020). Kyrgyzstan has over 3,500 rivers, with significant water use for irrigation (almost 95%) and limited industrial and domestic consumption (Osmonbetova, 2021). 84% of the total water consumption in Tajikistan is used for agriculture (Toderich, 2004). Turkmenistan primarily depends on the Amu Darya, with water intake governed by international agreements. Agriculture is the largest consumer, accounting for over 90% of water usage (Zonn, 2012). Uzbekistan relies on both the Amu Darya and Syr Darya, with irrigation making up about 86% of water consumption

(State water cadastre of Uzbekistan, 2014). Afghanistan is a key contributor to the Amu Darya's water supply, with the river originating from Lake Zorkul within its borders. However, due to limited agricultural and industrial development, largely resulting from decades of conflict, Afghanistan has historically used only a small share of the river's water compared to its Central Asian neighbors. In 2022, the Afghanistan initiated the Qosh Tepa Canal project, raising significant concerns—particularly from Uzbekistan, where impacts on the agriculture sector are anticipated. Overall, the distribution and management of water resources in Central Asia are complex, and influenced by climate variability, economic development, and inter-country agreements.

Table 1.3.1. Composition and volume of the main surface water resources of Central Asia (Safronova, 2009).

Country	Amu Darya basin $km^3\ yr^{-1}$	Syr Darya basin $km^3\ yr^{-1}$	Aral Sea basin $km^3\ yr^{-1}$	%
Kazakhstan	-	4.50	4.50	3.9
Kyrgyzstan	1.90	27.4	29.30	25.3
Tajikistan	62.9	1.1	64.00	55.4
Turkmenistan	2.78	-	2.78	2.4
Uzbekistan	4.70	4.14	8.84	7.6
Afghanistan	6.18	-	6.18	5.4
Central Asia	78.46	37.14	115.6	100.0

Climate change poses a threat to glacial ice and water resources (Fig. 1.1.2). Rapid glacier change will affect the hydrological regime of mountain catchments: as modeled by Huss and Hock (2018), annual runoff is expected to reach a maximum (due to increased melt), followed by a decrease as glaciers retreat. The timing of such "peak water" occurrence is controlled by the present-day amounts of ice (both in absolute terms and relative to the catchment area). Predictions suggest increased cryosphere melt runoff in spring and summer, in combination with heavy rainfalls this can lead to glacial lake outburst floods, debris flows, and landslides causing damage to settlements and agriculture (Kaser et al., 2010; Huss and Hock, 2018; Bolch et al., 2011; Erokhin et al., 2018). Conversely, runoff during dry summer months may decrease steadily by the end of the century due to decreasing ice volume (Hagg et al., 2007; Hagg et al., 2013; Huss and Hock, 2018; Kure et al., 2013).

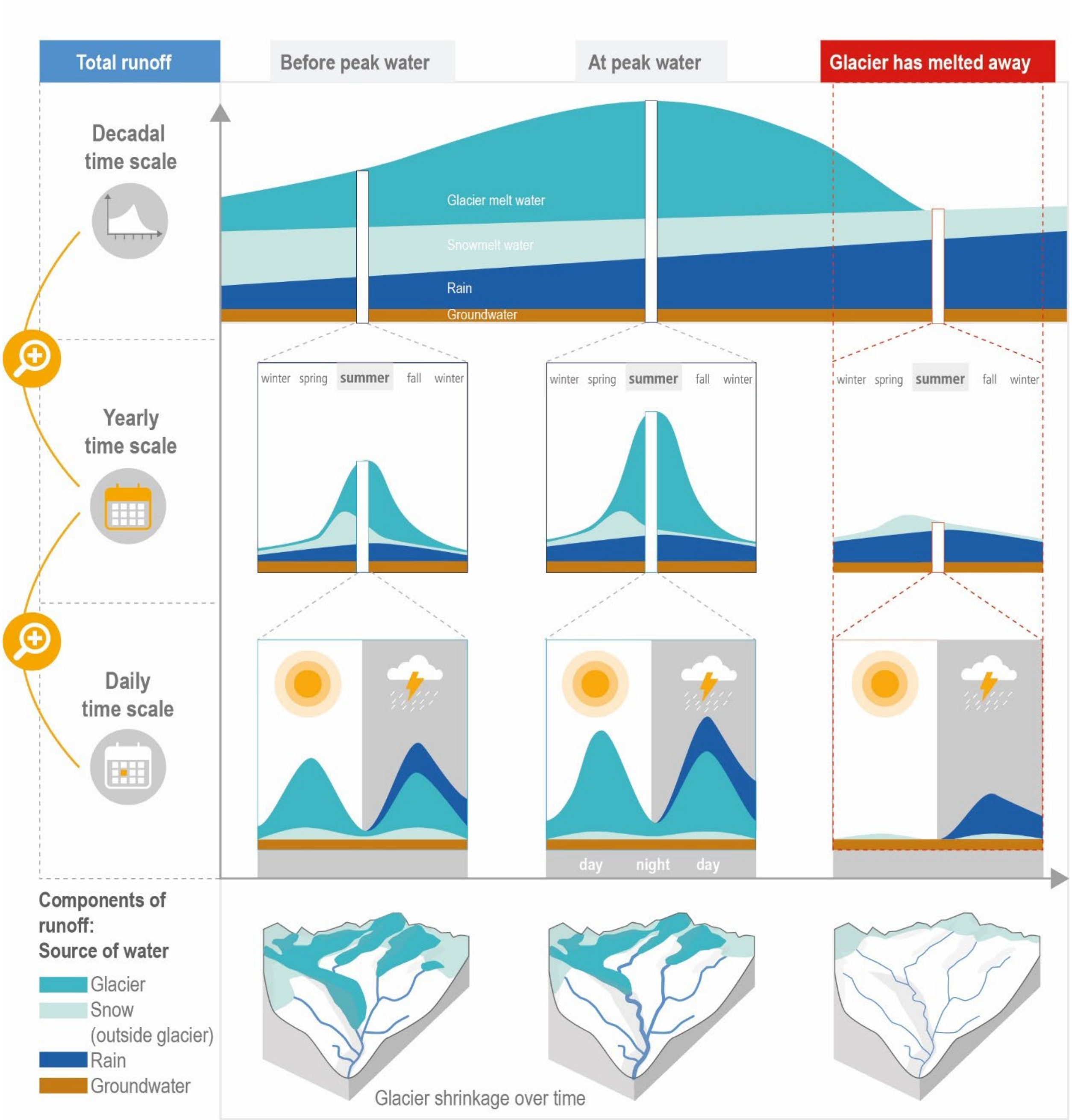

Figure 1.1.2. Schematic view of expected runoff changes under ongoing climate change: (a) affecting total glacier melt water contribution and (b) seasonality in water availability (Credits: IPCC 2021).

These predictions underscore the need for effective water management and monitoring of glacier mass balance in the region. Ongoing efforts since 2010 aim to re-establish in situ glacier monitoring, contributing to validating modeling studies and regional assessments of glacier behavior and its impact on freshwater resources in Central Asia (Hoelzle et al., 2017, 2019; Schöne et al., 2013).

CHAPTER 2: DATA & METHODS

Here, we rely on existing regional-scale glacier mass balance, glacier retreat and runoff model results that were achieved using the Global Glacier Evolution Model (GloGEM), developed at the University of Fribourg and the ETH Zürich GloGEM is a process-based model that accounts for all glaciological processes and aims at a worldwide application, even though resolving all individual glaciers specifically (Huss&Hock, 2015, 2018; Zekollari et al., 2019; Compagno et al., 2022). For the present analysis we analyze the GloGEM output related to the study by Bossons et al. (2023) for the RGI regions 13 and 14, that include the Tien Shan and Pamir mountain ranges. Below we summarise the data and methods used. A detailed description of the model can be found in the respective publications (Huss&Hock, 2015, 2018; Bosson et al., 2023).

2.1 Data

The **initial ice extent**, which refers to approximately 2000, is provided by the Randolph Glacier Inventory v.6.0 (RGI, 2017). The surface hypsometry for each glacier is derived from the intersection of the outlines with the SRTM digital elevation models (DEMs, Jarvis et al., 2008). Each glacier is discretized into surface elevation bands of 10 m. The bedrock topography is available from a consensus of five ice thickness models (Farinotti et al., 2019). These ice thickness models follow the approach of estimating of ice volume fluxes and the principles of flow dynamics. Evaluated at the global scale, the calculated thicknesses are in good agreement with observations (Farinotti et al., 2019).

Hugonnet et al. (2021) provided **glacier-specific observations of ice volume change** between 2000 and 2020 using a multi-source data approach to assess global glacier mass loss. The authors relied primarily on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite elevation data to calculate geodetic mass balances for glaciers in the study region for the period from 2000 to 2020. While satellite data, including ASTER and CryoSat-2, provide valuable elevation measurements, temporal coverage can be inconsistent, leading to potential gaps in the analysis (Nakamura et al., 2006). In addition, the resolution and quality of satellite imagery can affect the accuracy of these measurements, resulting in significant uncertainties in volume change estimates based on this dataset, especially for shorter time intervals (Hugonnet et al., 2021). Nevertheless, this dataset remains one of the most consistent and complete for assessing glacier volume change over the past two decades on a global scale.

Surface mass balance observations from **in situ measurements** on individual glaciers provided by the World Glacier Monitoring Service (WGMS, 2022) were used for model validation. For Central Asia, however, these observations remain severely limited in space and time, making robust model validation difficult for the Tien Shan and Pamir, especially considering the complete lack of observational data for certain subregions (Barandun et al., 2021).

For the future forecast, we use **climate time series** of gridded monthly 2m air temperature and precipitation from 56 climatic model chains (based on 13 different global climate models, or GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016) . The GCM results are based on three different Shared Socioeconomic Pathways (SSPs) describing future climate forcing due to different greenhouse gas emissions (SSP1-2.6, SSP2-4.5, SSP5-8.5) (Meinshausen et al., 2020). The scenarios are based on a range of projections of future population growth, technological development and societal responses (Meinshausen et al., 2011).

In the **SSP1-2.6 scenario**, which represents a low-emission pathway to achieve significant climate mitigation, radiative forcing is projected to increase by about 2.6 W/m² by 2100 compared to pre-industrial levels (IPCC, 2021). This scenario emphasizes sustainable development, strong climate policies, and a transition to renewable energy sources (Riahi et al., 2017).

The **SSP2-4.5 scenario**, represents a medium greenhouse gas emission pathway. It assumes an increase in radiative forcing of about 4.5 W/m² by 2100 compared to pre-industrial levels (IPCC, 2021). This scenario focuses on sustainability while facing moderate climate mitigation and adaptation challenges (Riahi et al., 2017).

In the **SSP5-8.5 scenario**, which represents a high emissions' pathway, radiative forcing is projected to increase by about 8.5 W/m² by 2100 relative to pre-industrial levels (IPCC, 2021). This scenario is characterized by rapid economic growth, heavy reliance on fossil fuels, and limited efforts to mitigate climate change, leading to significant greenhouse gas emissions (Riahi et al., 2017).

The climate time series are bias-corrected using gridded monthly temperature and precipitation data from the ERA5 reanalysis, which provides a comprehensive representation of past climate and weather conditions (Hersbach et al., 2020). For each glacier, additive (for temperature) and multiplicative (for precipitation) monthly biases are calculated between the closest ERA5 and the corresponding GCM grid cell for a given glacier for the period 1980 to 2020. These biases are then adjusted to account for the altitude distribution of the glaciers using constant precipitation and temperature gradients. During the projection period, the calculated biases - which are assumed to remain constant over time - are superimposed on the global climate model (GCM) series. To further refine the data, GCM air temperature values were adjusted to account for discrepancies in annual variability between the ERA5 and GCM time series (Huss and Hock, 2015). This adjustment is critical to ensure the validity of calibrated melt model parameters used in GCM-driven projections. However, a significant limitation is the inherent uncertainty in the variability represented by the reanalysis product, which can introduce biases into the corrected GCM time series and ultimately contribute to high uncertainty in the projections.

2.2 Glacier evolution model and calibration

Projections of future glacier volume change and meltwater release were made using the Global Glacier Evolution Model (GloGEM) (e.g. Hock and Huss, 2015, 2018, Compagno et al., 2021, 2022, Bosson et al., 2023). GloGEM is a model for calculating mass balance and associated geometric changes for each of the world's glaciers. The model describes the main processes that determine the climatic mass balance (Huss and Hock, 2015). The model operates on 10m elevation bands at the scale of every individual glacier in a region and has a monthly time resolution, including a parameterization of sub-monthly air temperature variability (Huss&Hock, 2015). Climatic mass balance (CMB) refers to the net change in the mass of a glacier over a given period of time, typically assessed on an annual or seasonal basis. It is a critical indicator of a glacier's response to climate variability and is used here to model glacier volume change. CMB can be expressed as the sum of all accumulation and ablation processes. Accumulation processes are all processes that add mass to a glacier. Ablation processes are all processes that remove mass from the glacier. In Central Asia, accumulation is mainly by snowfall, snow drift, refreezing of meltwater, and avalanches. The dominant ablation process is melting, followed by sublimation in more radiation-dominated areas. Melting and sublimation rates are determined by air temperature, solar radiation, surface albedo, and the vapour gradient between the surface and the atmosphere (Cuffy and Patterson, 2010).

Melting is calculated using a traditional temperature index model that distinguishes between snow melting and ice melting using two different empirical factors (Hock, 2003). Solid precipitation as a function of altitude and air temperature is used to model accumulation (Huss et al., 2009). The model is thus relatively simple and relies heavily on the relationship between air temperature and melt being linear and constant over time. Fundamentally, snow and ice begin to melt when the air temperature is above 0°C. Melting rates are proportional to air temperature, scaled by an empirical factor (degree-day factor). These factors differ depending on whether the surface is snow or ice. Typically, the degree-day factor is higher for ice, meaning that ice melts faster than snow at the same temperature due to lower albedo and thus higher energy intake. Solid precipitation occurs when the air temperature near the surface is above a certain threshold, typically 1.5°C. Wherever this condition is met on the glacier, precipitation is recorded as accumulation. Refreezing of liquid water in sub-zero snow or firn is modelled based on heat conduction and latent heat exchange (Huss&Hock, 2015). Other processes, such as mass gain or loss by avalanches are not explicitly resolved but will implicitly be taken into account via calibration on glacier-specific data. Radiation effects beyond the distinction of ice and snow melt are neglected. All processes and associated feedback are assumed to have a stable relation and respond like at present-day conditions over the next 100 years. The model does not account for basal mass balance. While GloGEM has a module accounting for the effect and the spatio-temporal dynamics of supraglacial debris (Compagno et al., 2022), this model version was not used here. Glacier surging is also not considered. For the determination of the degree-day factor and the refreezing model, the surface type (snow/firn/ice) is required. Following Hock and Huss (2015), at the start of the modelling process, the surface type is set at the end of summer by setting the firn line along the median glacier elevation, withbare ice below. Throughout the modeling year, the surface type is updated monthly for each elevation band based on the climatic mass balance. If the cumulative balance is positive, the surface is assigned as snow. Conversely, if it is negative, indicating that all the snow has melted, the surface is classified as bare ice or firn. Firn is classified if the average annual balance over the last five years is positive, otherwise, the surface is classified as ice. This method effectively approximates spatial and temporal variations in firn area without requiring a full firn compaction model (Huss and Hock, 2015).

The dynamic response of each glacier to changes in mass is simulated using an empirical relationship that describes thickness change as a function of normalized elevation range (Huss et al., 2010). At the end of each mass balance year, the model adjusts thickness, surface elevation and glacier extent depending on that year's computed total mass change of the respective glacier. Previous assessments indicate that this parametrized approach to model three-dimensional glacier evolution agrees well with more complex ice-dynamical modeling (Huss et al., 2010). For more information on the model description and parameterization of the different processes taken into account in GloGEM, see Huss and Hock (2015).

Runoff is computed as the sum of snow-/icemelt, liquid precipitation minus refreezing over a virtual catchment area that corresponds to the initial extent of each individual glacier. At the beginning of the modelling period, this catchment is 100% glacierized but evolves to a basin with partial glacier cover during retreat. This approach thus allows considering a stable area for runoff generation, i.e. the headwater of large streams, but does not make direct statements about larger-scale hydrological processes, also involving vegetation and groundwater dynamics, which could only be tackled with a full hydrological model.

One of the primary challenges facing regional to global glacier models is their calibration. This process is essential because neither the downscaled meteorological variables accurately represent site-specific conditions, nor can the glacier models effectively capture the complex processes affecting each glacier with precision (Huss and Hock, 2015). Most global glacier models have relied on in situ mass balance records as the main source of calibration data (Radić and Hock, 2011; Giesen and Oerlemans, 2013). In certain studies, model parameters were further refined to align with estimates of regional mass changes derived from extrapolated glacier observations (Radić et al., 2014). However, calibrating such a model for Central Asia using in situ mass balance data from individual glaciers presents challenges. Direct observations are often limited to relatively small glaciers, while regions with significant ice cover are frequently under-sampled (Huss and Hock, 2015). GloGEM has thus been calibrated for each glacier individually to glacier-specific remote sensing observations of ice volume change between 2000 and 2019 (Hugonnet et al., 2021) according to a multi-step procedure (Huss and Hock, (2015). If the modelled glacier-wide specific mass balance agrees with the specific balance provided in Hugonnet et al., (2021) within a threshold set to ±0.1 m w.e. a^{-1}, the meteorological forcing series is considered to describe the climatic conditions for this glacier well. The calibration is thus interpreted as a second downscaling step that removes the effect of inherent imprecisions in the regional-climate-forcing products (Bosson et al., 2023). Modeled mass balance components have been validated in detail with independent observations (for example, mass balance, area change, Huss and Hock, 2015, 2018). The model reproduces independent datasets of observed mass balance worldwide (WGMS, 2022), for both annual glacier mass loss and seasonal components and elevation dependencies (Bosson et al., 2023).

Once the model has been calibrated for the period 2000 to 2020, it is subsequently run with ERA5 reanalysis data from 1980 to 2020 and then with downscaled GCM data until 2100. Mass-balance changes are then assessed for all regions over the period from 1980 to 2100. Projections of future glacier retreat by GloGEM provide changes in glacier mass balance, area, volume, and water runoff at monthly/annual resolution and for every single in the investigated region (Tien Shan/Pamier) until 2100.

Catchment boundaries in order to determine the glacier meltwater contribution are delineated according to hydrological routing on the surface DEM (Table 2.2.1 and 2.2.2, Ehlschlaeger (1989)). Catchments include all the largest rivers contributing to Amu Darya and Syr Darya, as well as other major independent rivers in Central Asia (such as Zeravshan) and the endorheic basins of lakes Issyk-Kul in Kyrgyzstan and Karakul in Tajikistan. To improve robustness of the results, for each catchment we took the median result of the GloGEM simulation over 13 GCMs.

Table 2.2.1: Description of each catchment used to calculate ice volume change and glacier meltwater contribution to total river runoff.

ID	name	description	contents	Other catchments upstream that contribute to the meltwater contribution of this catchment
01	amudarya	Amu Darya downstream of Kofarnihon inflow	Other: Only Afghan territory	02,03,04,05,06,07,08,09,10,11,12,13,14,15
02	kofarnihon	Kofarnihon	Glaciers: Yakarcha; Cities: Dushanbe	
03	panj	Panj upstream of confluence with Vakhsh	Cities: Kulob	04,05,06,07,08,09,10
04	vanchob	Vanchob	Glaciers: Medvezhy	
05	panj	Panj upstream of Vanchob inflow	Glaciers: Yazgulem	06,07,08,09,10
06	bartang	Bartang	Cities: Murghab; Other: Sarez lake	
07	gunt	Gunt	Glaciers: #457; Cities: Khorog	
08	panj	Panj upstream of Gunt inflow	Cities: Ishkashim	09,10
09	wakhan	Wakhan	Other: Wakhan corridor	
10	pamir	Pamir	Other: Wakhan corridor	
11	vakhsh	Vakhsh upstream of confluence with Panj	Other: Nurek reservoir	12,13,14,15
12	khingov	Khingov	Glaciers: Garmo	
13	vakhsh	Vakhsh upstream of Khingov inflow	Other: Alai ridge south	14,15
14	muksu	Muksu	Glaciers: Fedchenko, Kyzylsu; Other: Pik Lenin south	
15	kyzylsu	Kyzylsu	Glaciers: Abramov; Other: Alai valley, Pik Lenin north	
16	syrdarya	Syr Darya at Chardara reservoir	Glaciers: Barkrak; Cities: Khujand, Tashkent; Other: Chardara reservoir	17,18,19,20
17	syrdarya	Syr Darya at Kairakum reservoir	Cities: Kokand; Other: Ferghana valley, Kairakum reservoir, Alai ridge north	18,19,20
18	karadarya	Kara Darya	Cities: Uzgen, Andijon	
19	naryn	Naryn upstream of confluence with Kara Darya	Cities: Naryn; Other: Toktogul reservoir	20
20	karasay	Karasay	Glaciers: Batysh Sook, Grigoriev, #354, Sary-Tor, Bordu; Other: Kumtor mine	
21	zeravshan	Zeravshan	Glaciers: Zeravshan, GGP	
22	chuy	Chuy	Glaciers: Golubin; Cities: Bishkek	
23	kaskelen	Kaskelen	Glaciers: Tuyuksu; Cities: Almaty	
24	karakul	Karakul	Glaciers: Zulmart, Kon-Chukurbashi; Other: Karakul lake	
25	issykkul	Issyk-Kul	Glaciers: #599, Kara-Batkak, Turgen-Aksu; Other: Issyk-Kul lake	

Table 2.2.2: Total catchment area, total catchment area including upstream catchments. Glaciated area in each catchment, glaciated area including upstream catchments and glaciated area in the catchment as well as including upstream catchments in percentage are shown here.

ID	name	total area (km^2)	cumulative total area (km^2)	Glacierized area (km^2)	cumulated glacierized area (km^2)	glacierizedarea [%]	cumulated glacierized area [%]
01	amudarya	41363	208328	98	9714	0.24	4.66
02	kofarnihon	11347	11347	93	93	0.82	0.82
03	panj	48416	116795	741	5538	1.53	4.74
04	vanchob	2096	2096	342	342	16.34	16.34
05	panj	8469	66283	449	4455	5.31	6.72
06	bartang	28014	28014	1684	1684	6.01	6.01
07	gunt	13690	13690	651	651	4.76	4.76
08	panj	6812	16110	620	1671	9.10	10.37
09	wakhan	4755	4755	725	725	15.25	15.25
10	pamir	4544	4544	326	326	7.17	7.17
11	vakhsh	9808	38823	0	3985	0.0	10.26
12	khingov	6577	6577	843	843	12.82	12.82
13	vakhsh	7186	22437	384	3142	5.34	14.00
14	muksu	6920	6920	2177	2177	31.46	31.46
15	kyzylsu	8330	8330	580	580	6.97	6.97
16	syrdarya	44379	168648	154	1852	0.35	1.10
17	syrdarya	40302	124269	603	1698	1.50	1.37
18	karadarya	23198	23198	78	78	0.34	0.34
19	naryn	58112	60769	707	1017	1.22	1.67
20	karasay	2657	2657	310	310	11.67	11.67
21	zeravshan	11741	11741	562	562	4.79	4.79
22	chuy	26886	26886	358	358	1.33	1.33

23	kaskelen	3868	3868	40	40	1.04	1.04
24	karakul	4467	4467	384	384	8.59	8.59
25	issykkul	21934	21934	502	502	2.29	2.29

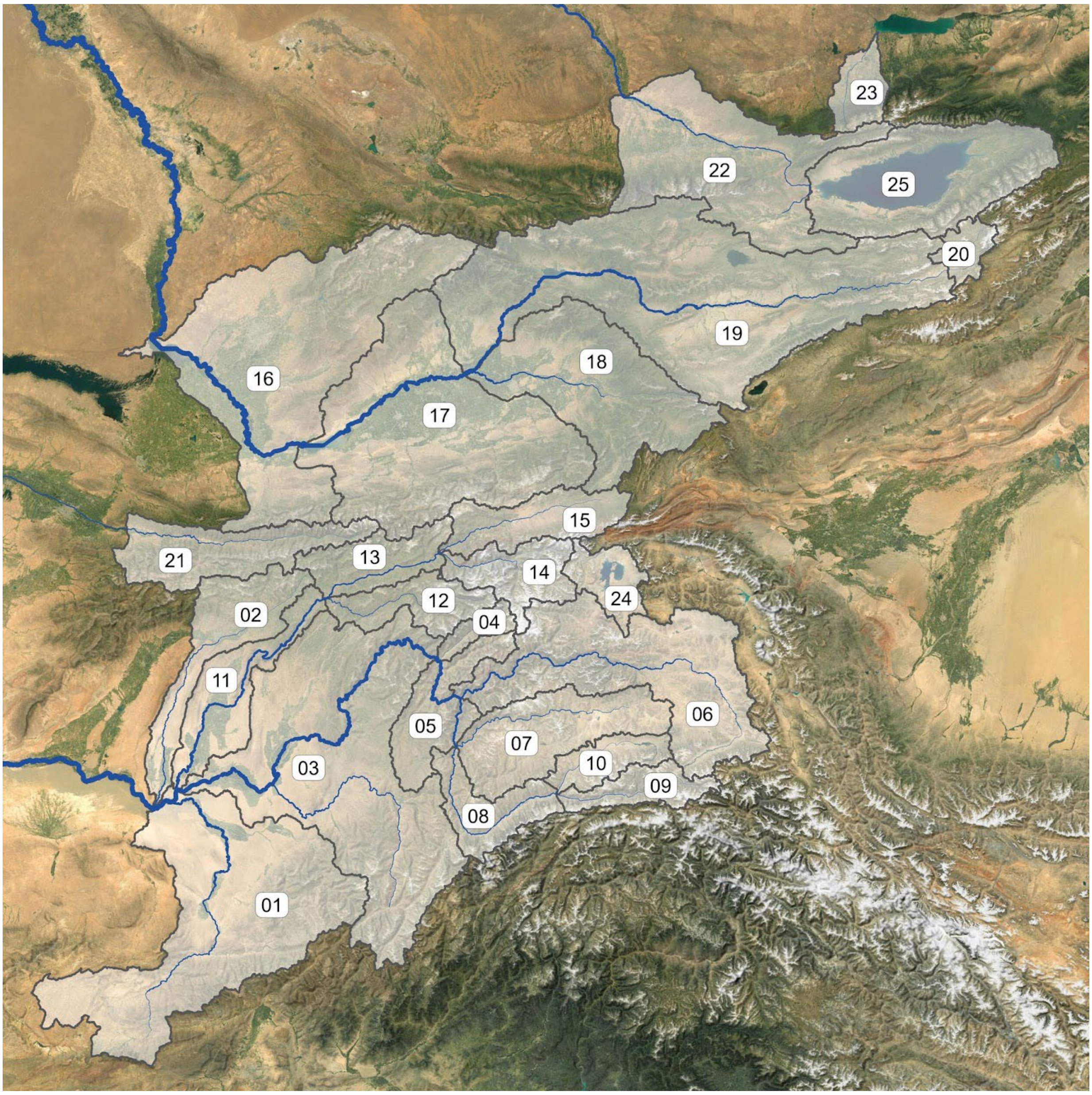

Fig. 2.2.1: Figure showing the geography of the catchments with their ID provided in Table 2.2.1.

2.2 Model uncertainty

Our results on future glacier retreat are subject to considerable uncertainty. While combined modeling and remote sensing studies have reconstructed region-wide cryosphere response to climate change for the past (e.g., Barandun et al., 2021; Gruber, 2012; Mankin & Diffenbaugh, 2015, Van Tricht et al., 2021, Farinotti et al., 2015)), future prediction relies on models based on today's cryosphere data. For regions with little data, large uncertainties persist and result interpretation has do be handled with care. A dominant source of uncertainty for cryosphere modeling is meteorological forcing. Future projections of cryosphere changes rely on predictions of climate drivers from downscaled Global Climate Models (GCMs, Hock et al., 2019). The spatial resolution of GCMs (100-300km) can lead to considerable biases in modeled climate data for topographically complex areas where surface and subsurface conditions may vary strongly over short horizontal distances (Gubler et al., 2011). Some Regional Climate Models (RCMs) have been recently developed for Central Asia to derive regional climate fields at a finer resolution of several tens of km (Ozturk et al., 2012; Russo et al., 2019). Unlike the understanding of the large-scale circulation system, assessment of regional- and local-scale climate conditions remains very difficult (Zandler et al., 2019). Continuous high-resolution (10-100m) climate fields are required to simulate local slope-scale processes. Uncertainties remain thus large, especially considering precipitation. In this context, reanalyses produced by atmospheric models, with spatial resolutions typically in the range of 10 – 50 km, represent an essential data source to fill the lack of current climate information and correct potential biases in future simulations (e.g., Pereira-Cardenal et al., 2011; Maussion et al., 2014). Mostly, these require preliminary downscaling to increase the representativeness of local scale patterns, using ground station data. The challenge is the lack of in situ meteorological data to assess the quality and biases of representative climate forcing (Unger-Shayesteh et al., 2013).

It is now a priority to produce adequate climate time series for past, present, and future modeling. Inverse methods and proxy parameters such as snow cover (Molotch, 2010; Margulis et al., 2015; Aalstad et al., 2018) or glacier mass balance (Immerzeel et al., 2015) have the potential to improve debiasing (e.g., precipitation field). Ensemble-based data assimilation approaches have the advantage of directly quantifying uncertainties related to the forcing, samples, and models (Fiddes et al., 2019). These research lines need to be pushed forward for Central Asia.

Bosson et al. (2023) discussed the impact of uncertainties stemming from (1) greenhouse gas emission scenarios; (2) GCM projections; (3) data on initial glacier area, ice thickness, and past glacier changes; and (4) simplifications in the glacier model and calibration procedure. They identified five key elements contributing to the overall uncertainty in their glacier evolution model and re-ran it with conservative assumptions to examine their influence on the final results. The experiments focused on the effects of (1) uncertainty in glacier-specific geodetic mass balance; (2) the chosen calibration period (2000–2019 versus 2000–2009 or 2010–2019); (3) the precipitation correction factor for each glacier; (4) melt factors for snow and ice; and (5) uncertainty in initial glacier volume (Farinotti et al., 2019; Milan et al., 2022). The individual impacts on future glacier ice volume were combined into an integrated uncertainty using the root sum of squares. To assess uncertainties in model calibration data, Bosson et al. (2023) assumed these uncertainties to be independent among glaciers. However, they noted that uncertainties in glacier models toward the end of the twenty-first century are constrained by the complete loss of smaller glaciers, regardless of model assumptions (Bosson et al., 2023). Regional results indicated that differences in SSP forcing and the spread among GCMs using the same SSP are the dominant sources of uncertainty in projected glacier volume evolution for the century, aligning with findings from previous studies (Marzeion et al., 2020). Additional uncertainties, particularly systematic errors are difficult to evaluate at the global scale, and may require further investigation, such as downscaling of meteorological variables and addressing parameter equifinality in model calibration (Rounce et al., 2023; Compagno et al., 2021).

It is important to recognize the limitations of future glacier mass balance models, particularly those using temperature index approaches. These models often use simplified process representations that do not take into account the non-linear responses of glaciers and their feedback mechanisms to changing atmospheric conditions. For example, as air temperatures increase, firn exposure during the ablation season is likely to increase due to complete depletion of the snowpack. This shift can alter the surface albedo, refreezing capacity and thus affect melt rates to some degree. Different mass balance and firn processes related to changing firn surface conditions are so far not well understood and thus difficult to account for in future prediction (Machguth et al., 2023, Kronenberg et al., 2022). Similarly, the spatial and temporal heterogeneities of the albedo are not considered (Naegeli et la., 2019, Volery et al., accepted). In addition, changes in climate regimes may alter the sensitivity of the mass balance, shift glacier responses from sublimation-dominated to melt-dominated ablation, or alter refreezing patterns. The increasing frequency of precipitation events on glaciers adds another layer of complexity, as the thermal effects of these precipitation events are also overlooked in such models. The simplification and omission of many complex processes and feedbacks can drastically alter the response of glaciers to climate change.

Many of these interactions are not fully understood, nor represented in current modeling efforts, leading to significant uncertainties in future scenarios of ice volume changes and glacier meltwater contributions. Consequently, the results of these models should be interpreted with caution and as trends rather than precise quantifications of change. New datasets of glacier thickness, derived from multi-model approaches and validated with extensive local observations (Rounce et al., 2023, Farinotti et al., 2019, Welty et al., 2020), have reduced uncertainties in the knowledge of current glacier thickness and, consequently, of future bedrock topography compared to earlier assessments.

Calculating the contribution of glacier meltwater to various catchments necessitates careful consideration of catchment delineation and river routing, which may not align with current surface topography. Inaccurate routing can lead to significant errors in estimating glacier meltwater contributions for specific basins. For instance, the Fedchenko Glacier, one of the largest glaciers outside the polar regions, exemplifies this complexity. It is crucial to understand the future drainage basin for meltwater to accurately forecast meltwater inputs into the river systems of the Pamir region.

Currently, Tanymas Lake, formed by an ice dam of glacier Tanymas-5, receives meltwater from the Fedchenko Glacier. With an area of 1 km², this lake has the potential to drain into two distinct catchments: to the east towards the Panj River or to the north towards the Vakhsh River. This situation complicates the attribution of ice volumes and runoff to respective catchments, particularly in future projections. While it is likely that the ice dam will retreat significantly before the Fedchenko Glacier, both the glacier and lake levels are expected to decline. Although the immediate impact on the attribution of ice volumes is minimal, the relative significance of the Fedchenko Glacier's volume is expected to increase until 2100, as other glaciers in the region recede more rapidly.

There are many limitations associated with future modelling, but the glacier evolution model used here is a first step towards predicting the future response of glaciers to climate change and improving understanding of the coming changes in the cryosphere and their impact on water availability. Cryosphere-related issues will become increasingly relevant in the context of future climate change and require a better understanding of cryospheric processes for improved modelling through long-term observations.

CHAPTER 3: FUTURE CLIMATE AND GLACIER CHANGES IN CENTRAL ASIA

3.1 Future climate changes

Figure 3.1.1 and 3.1.2 show the temperature and precipitation change by the end of the century for the three different scenarios published in Siegfried et al., (2024)

Kazakhstan: Surface air temperatures in Kazakhstan are projected to rise in all seasons, with mid-century increases of 2.3-2.6°C under the SSP2-4.5 scenario and 3.0-3.5°C under the SSP5-8.5 scenario. By the end of century, these increases could reach 3.3-3.9°C and 6.2-7.3°C, respectively. The highest emissions scenario predicts an increase of over 6 °C, emphasizing the need for global emissions control to mitigate warming. Warming is expected to be more pronounced in the northern regions, and the likelihood of heat waves will rise significantly under high emissions scenarios (The 8th National Communication of Kazakhstan to the UNFCCC, 2022). Precipitation forecasts indicate an average increase of 7-8% by mid-century, potentially rising to 11-14% by the century's end. However, changes will vary regionally, in the west th increase is expected smaller than 10%, while in the southeast larger than 20%. Seasonal variations show significant winter increases (20-35%) and summer decreases (12% on average), with extreme precipitation likely to intensify (The 8th National Communication of Kazakhstan to the UNFCCC, 2022).

Kyrgyzstan: On average for Kyrgyzstan in 2100, a temperature increase of 6.1 °C is expected under the intermediate (SSP2-4.5) scenario and 4.7 °C under the mild scenario (SSP1-2.6). Under the pessimistic scenarios (SSP5-8.5) heat waves and other climate extremes will cause a severe threat to the ecosystem and threaten the livelihood in the affected regions considerably (Abdyrasuova et al., 2011). It has been estimated that heat waves will increase and 20-30% of summers will be significantly warmer in a 2 °C world while in a 4 °C world 50-80% of summers will be significantly hotter for the last quarter of the 21st Century (Reyer et al., 2015). Future projections on precipitation suggest that central and, especially, eastern Kyrgyzstan might become wetter (Reyer et al 2015). The changes in precipitation in a multi-model run are far more pronounced during the winter (DJF) than during summer (JJA) (Reyer et al 2015). Though analysis of precipitation records across country suggest precipiation increase in spring rather than winter, though the increases are insignificant (Third National Communication of the Kyrgyz republic, 2016). Apart from changes in precipitation Kyrgyzstan will probably experience increased aridity in lower lying areas due to increased evapotranspiration as a result of rising temperatures.

Tajikistan: average annual temperatures are projected to rise by 2°C by 2050, with significant increases expected between December and August (Climate Change Knowledge Portal WB). Historical analyses show a steady increase in air temperatures at a rate of 0.2 to 0.25°C per decade over the past 60 years, particularly in the western regions, while the eastern areas the temperature increase is less pronounced. From 2011 to 2041, warming trends do not significantly differ across emission scenarios. However, from mid-century (2041-2070), temperatures are expected to rise notably, ranging from +1.1 to +2.8°C under RCP8.5, with a significant increase by the end of the century (2071-2099) projected between +4.8 and +6.6°C (Aalto et al., 2017). Precipitation changes are less clear, with models offering conflicting predictions. Generally, a decrease in precipitation is anticipated in the western part of the country, while the mountainous eastern region may see slight increases, though these changes are minor due to already low annual totals (less than 100 mm) (Aalto et al., 2017). Climate warming is expected to lead to earlier snowmelt in spring, increasing the risk of flooding (Xenarios et al., 2019).

Turkmenistan: Analyzing climate change trends in Turkmenistan reveals spatial variability and data interpretation challenges. Research indicates that Central Asian deserts may become less arid due to global warming, potentially leading to a southward shift and intensification of westerly cyclones, reminiscent of early Holocene conditions (Lioubimtseva & Cole, 2006). Climate models predict temperature increases of 1-2°C by 2030–2050, but precipitation projections remain variable and uncertain (Lioubimtseva & Cole, 2006). The REMO 0406 scenario simulation suggests a significant temperature increase of 0.51°C per decade from 2016 to 2055, with expected decreased snow cover and increased evaporation along the Karakum Canal, resulting in significant reductions in available water resources (Duan et al., 2019). Climate records near the Aral Sea since the 1960s indicate a shift towards a more continental climate, characterized by increased summer temperatures, decreased winter temperatures, and altered precipitation patterns (Middleton, 2002). The shrinking surface area of the Aral Sea has been linked to decreased precipitation and saline dust, influencing rapid climate and vegetation changes (Glazovsky, 1995). While a rise in air temperatures is anticipated for Central Asia, the aridity index shows inconsistent trends across the region (IPCC, 2001). Remote sensing data indicate decreasing aridity in northern regions and a southward shift of the desert zone (Zolotokrylin, 2003), supported by findings from Kharin et al. (1998) that suggest a potential decrease in aridity in recent decades.

Uzbekistan: Future projections of climate change in Uzbekistan focus primarily on surface temperature and precipitation. Radchenko et al. (2017) forecasted changes in runoff in the Syr Darya basin, anticipating temperature increases (3.7°C to 3.9°C) and precipitation rises (11% to 13%). The impacts of global warming on glaciers in Central Asia, including Uzbekistan, have been studied extensively (Sorg et al., 2012a; 2014; 2015; Kure et al., 2013; Barandun et al., 2020), with Sorg et al. (2014) predicting significant glacier shrinkage due to rising temperatures in the Tien Shan Mountains, which are vital for regional water supply. The negative consequences of climate change on agriculture and food security in Central Asia have been explored by Sommer et al. (2013) and Bobojonov and Aw-Hassan (2014). Finally, reviews by Xenarios et al. (2019) have summarized existing literature on the impacts of anthropogenic climate change and adaptation measures in the region.

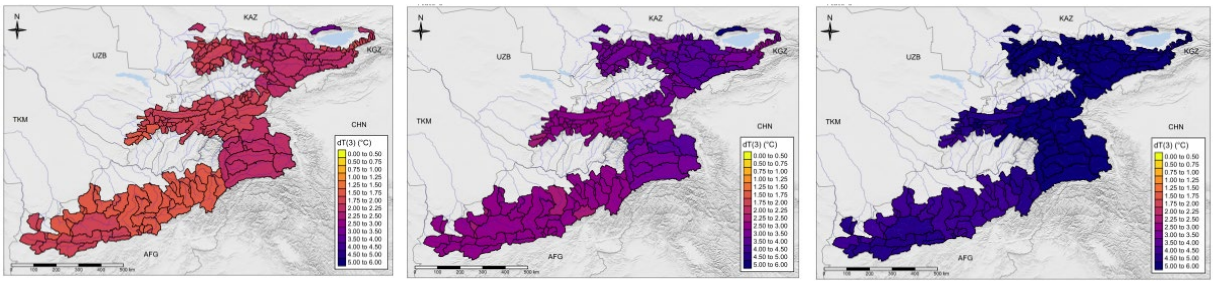

Figure 3.1.1: Temperature change for Central Asia for the three emission scenarios by 2100 from Siegfried et al., 2024.

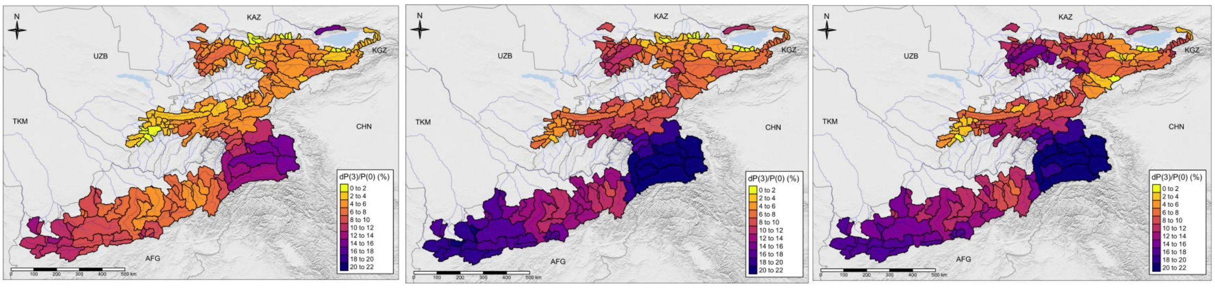

Figure 3.1.2: Precipitation change for Central Asia for the three emission scenarios by 2100 from Siegfried et al., (2024).

3.2 Future ice volume changes

Until the end of the 21st century, glaciers in the Tien Shan and Pamir are expected to continue the current, accelerating trend of mass loss (Rounce et al., 2023). Our results indicate a total ice volume loss ranging from 58% (low-emission scenario) to 85% (high-emission scenario) of the total ice volume in 2020 by 2100 (Fig. 3.2.1). For the high emissions scenario, for example, this means that only about 140km3 of the present 860km3 ice mass will remain.

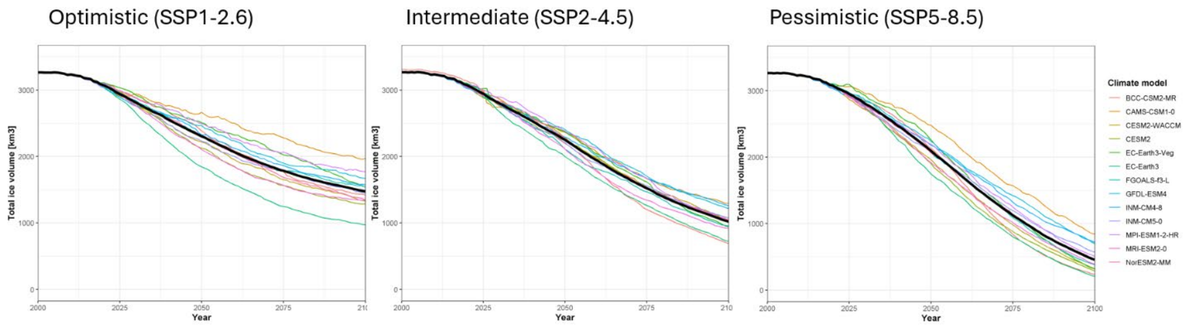

Figure 3.2.1: Simulated ice volume change in RGI region 13 from 2000 to 2100. The black line shows the average from all 13 climate models (in colour) for the three different scenarios. All scenarios show a strong ice volume loss.

Glacier volume loss will accelerate until mid-century and then slow slightly (Fig. 3.2.2). For the Tien Shan (Syr Darya basin), ice volume loss is greatest until 2040, after which it slows. This is not due to a decrease in atmospheric warming, but rather to a large reduction in ice volume, leaving less ice for melting. For most basins in the Pamir (Amu Darya Basin), the relative volume loss is more stable, and the relative ice volume loss decreases only slightly until the end of the century (Fig. 3.2.2).

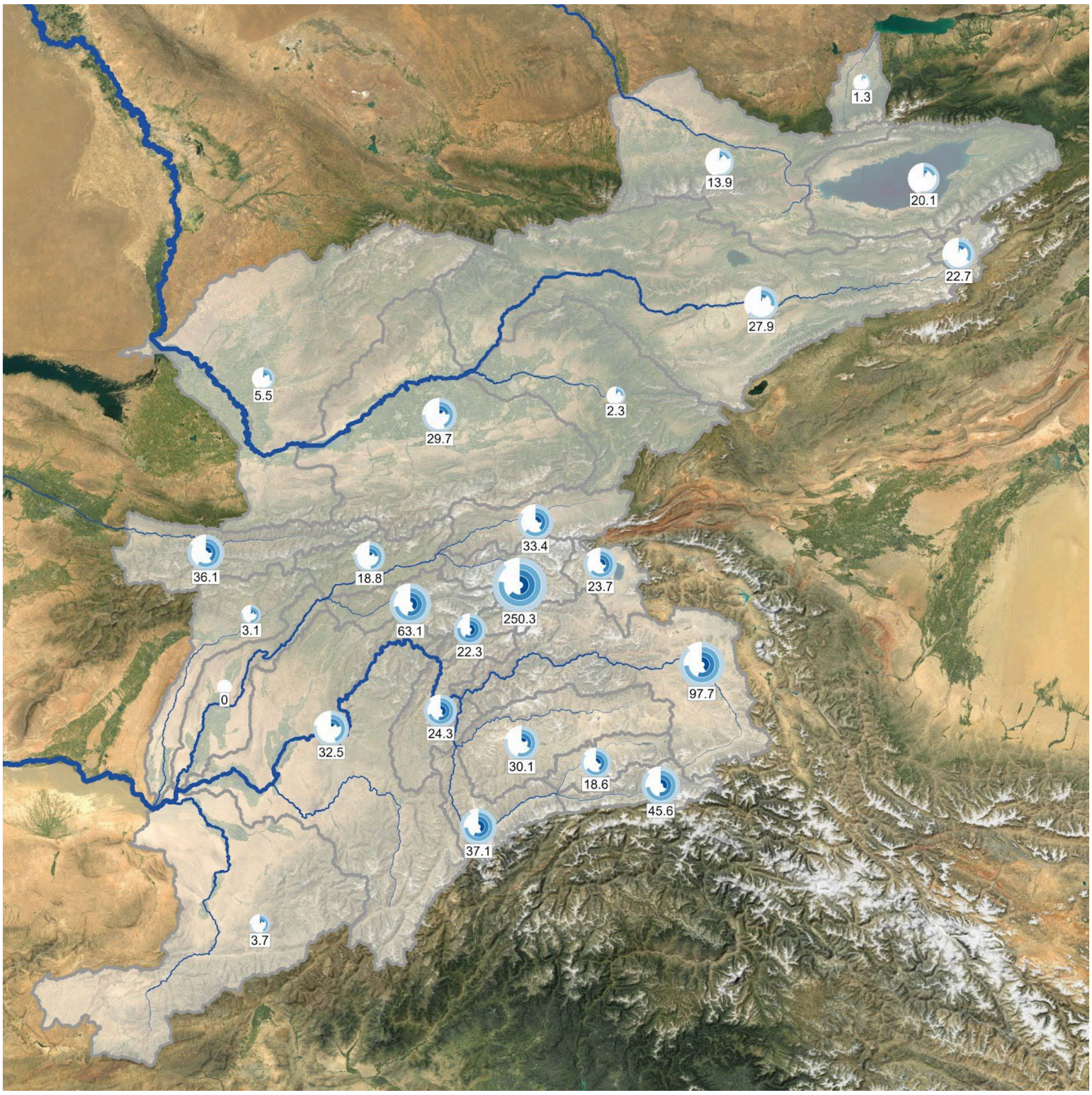

Figure 3.2.2: Catchment-wide volume loss for the intermediate scenario (SSP2-4.5). The blue colour in the pie charts indicates the volume change by 2040, 2060, 2080 and 2100 (from lightest to darkest blue) relative to the ice volume in 2020 (numbers below the pie chart).

Glacier mass loss is spatially heterogeneous across Central Asia (Fig. 3.1.2 and Table 3.1.1). The smallest and lower-lying glaciers are projected to disappear well before 2100, even in the low emissions scenarios, whereas the largest and higher-lying glaciers are projected to persist into the 22nd century, even in the more pessimistic projections, albeit with volume losses of more than 50%. Therefore, the western margins of both the Tien Shan and the Pamir are more affected by ice volume loss by the end of the century than for example the interior regions of Tien Shan and Pamir. The outer orographic margin of the Tien Shan and Pamir are regions that currently receive a greater proportion of precipitation due to a westerly blocking effect caused by topography. However, glaciers in this region are located at lower altitude and consequently higher mean annual air temperatures. Increasing air temperature trends will thus have stronger impacts on the retreat rates in this region.

There is in a sharp contrast in predicted ice volume loss between the catchments in the Central Asian Tien Shan and Pamir (Fig. 3.2.3). This is evident for all scenarios. Glacier ice will remain in the Amu Darya basin and the Karakul catchment until the end of the century, especially in the central Pamir, where the Fedchenko glacier holds much of the ice volume. For the Central Asian Tien Shan, ice volume retreat is predicted to be as high as 70% under the most favourable scenarios, while glaciers in this region will disappear completely under the high emissions scenario (Fig. 3.2.2 and S5 for the other scenarios). In this scenario, glaciation will be strongly reduced across the region, remaining only at very high elevations.

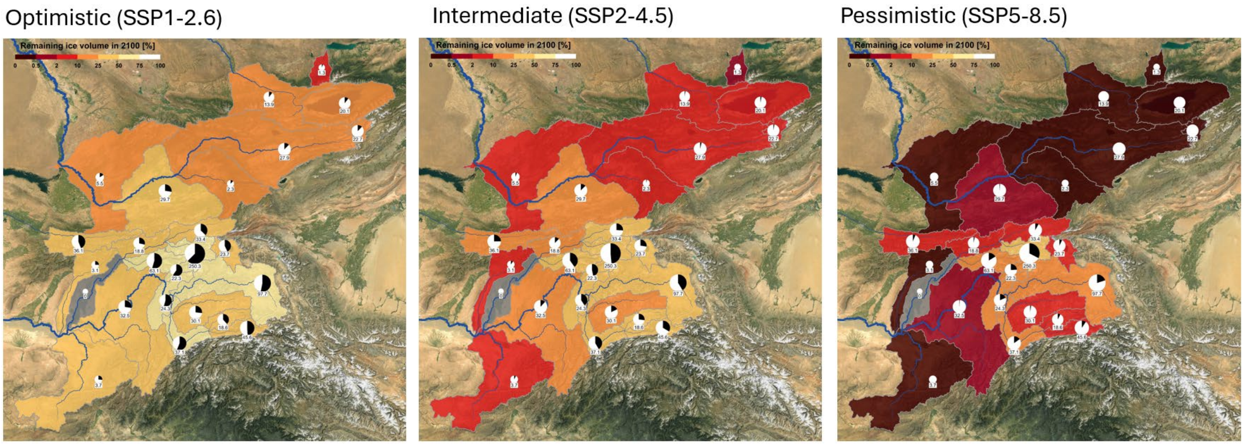

Figure 3.2.3: Catchment-wide glacier volume loss. Pie charts show the total volume remaining in black by 2100 and the total volume lost in white. Numbers below the pie charts indicate the ice volume in 2020.

Table 3.2.1: Relative ice volume change in relation to the 2020 ice volume for all three emission scenarios.

Optimistic (SSP1-2.6)

Watershed	2020	2040	2060	2080	2100
	km^3	%			
Amu Darya	**681**	**87**	**73**	**60**	**52**
Kofarnihon	3	70	53	36	26
Panj	308	86	70	52	45
Vanchob	22	87	77	66	60
Bartang	98	89	75	60	53
Gunt	30	78	54	35	27
Wakhan	46	88	70	60	49
Pamir	19	83	62	49	38
Vakhsh	366	88	76	64	57
Khingov	63	89	73	61	55
Muksu	250	90	80	70	62
Kyzylsu	33	82	63	47	37
Syr Darya	**88**	**66**	**42**	**24**	**19**
Kara Darya	2	54	30	18	13
Naryn	**51**	**63**	**38**	**20**	**12**
Karasay	23	68	42	23	12
Zeravshan	36	82	63	52	44
Chuy	14	49	23	13	10
Kaskelen	1	44	14	8	6
Karakul	24	84	68	50	43
Issyk-Kul	20	50	25	13	11

Intermediate (SSP2-4.5)

Watershed	2020	2040	2060	2080	2100
	km^3	%			
Amu Darya	**681**	**87**	**69**	**51**	**36**
Kofarnihon	3	78	51	23	10
Panj	308	86	69	50	35
Vanchob	22	92	77	60	47
Bartang	98	89	74	55	41
Gunt	30	79	55	34	18
Wakhan	46	88	73	52	33
Pamir	19	85	65	42	27
Vakhsh	366	88	72	56	41
Khingov	63	87	72	54	40
Muksu	250	90	78	63	48
Kyzylsu	33	84	63	40	26
Syr Darya	**88**	**70**	**37**	**17**	**7**
Kara Darya	2	57	25	8	3
Naryn	**51**	**65**	**31**	**11**	**3**
Karasay	23	69	35	12	3
Zeravshan	36	83	60	40	25
Chuy	14	53	19	6	2
Kaskelen	1	42	10	4	1
Karakul	24	84	64	43	27
Issyk-Kul	20	53	20	7	3

Pessimistic (SSP5-8.5)

Watershed	2020	2040	2060	2080	2100
	km^3	%			
Amu Darya	**681**	**85**	**60**	**37**	**21**
Kofarnihon	3	71	27	6	0
Panj	308	83	54	31	14
Vanchob	22	89	67	44	24
Bartang	98	86	61	39	20
Gunt	30	74	40	14	2
Wakhan	46	84	57	32	9
Pamir	19	80	51	28	8
Vakhsh	366	87	66	43	26
Khingov	63	83	61	36	16
Muksu	250	89	71	50	33
Kyzylsu	33	80	49	22	8
Syr Darya	**88**	**62**	**27**	**5**	**1**
Kara Darya	2	48	16	2	0
Naryn	**51**	**56**	**23**	**3**	**0**
Karasay	23	60	26	3	0
Zeravshan	36	81	50	24	6
Chuy	14	44	12	1	0
Kaskelen	1	35	5	1	0
Karakul	24	81	52	25	7
Issyk-Kul	20	44	12	2	0

CHAPTER 4: FUTURE CHANGES GLACIER METLWATER CONTRIBUTION IN CENTRAL ASIA

4.1 Annual meltwater contribution

Predicted changes in glaciers are expected to significantly affect the hydrological regimes of mountain catchments. As glaciers lose ice volume, the release of meltwater will increase, initially at an accelerated rate until 'peak water' is reached (Huss&Hock, 2018). After this point, the contribution of glacier melt will begin to decline due to the reduction in their size, with snowmelt and, in some cases, rain becoming the dominant contributors (Kaser et al., 2010). This shift will alter both the storage capacity and runoff patterns of affected regions, with important implications for water resource management. The timing of peak glacier meltwater contribution is influenced by the rate of warming (Rounce et al., 2023), but is also largely dependent on the current volume of ice, both in absolute terms and relative to the size of the catchment. The largest glacier complexes in the Pamir are not expected to reach peak discharge until 2100, while smaller, less glacierized catchments may have already passed their maximum discharge. As shown in Figure 4.1.1 and Fig. S1, none of the modelled catchments have yet reached peak glacier discharge. However, several catchments in the Syr Darya basin are approaching their peak meltwater contribution soon. For example, Kaskelen, Chuy and Issyk Kul are about to reach peak meltwater contribution, while Kara Darya, Naryn and Karasay are expected to do so within the next decade. Other catchments in the Syr Darya basin are projected to reach peak flow by mid-century. Thereafter, glacial meltwater input to the major rivers in the Syr Darya basin will soon begin to decline (Fig. 4.1.1). In contrast, the Amu Darya basin and its associated catchments are expected to reach peak flow later. Some, such as the Vanshob and Muksu, may not reach maximum meltwater input until the end of the 21st century, with meltwater contributions possibly continuing to increase into the 22nd century. Furthermore, while the decline in annual meltwater contribution after peak flow is expected to be more abrupt for the Syr Darya sub-basins, the decline in the Amu Darya basin may be more gradual. As a result, changes in river discharge are likely to be much more pronounced in the Syr Darya, while more gradual shifts are expected in the Amu Darya basin.

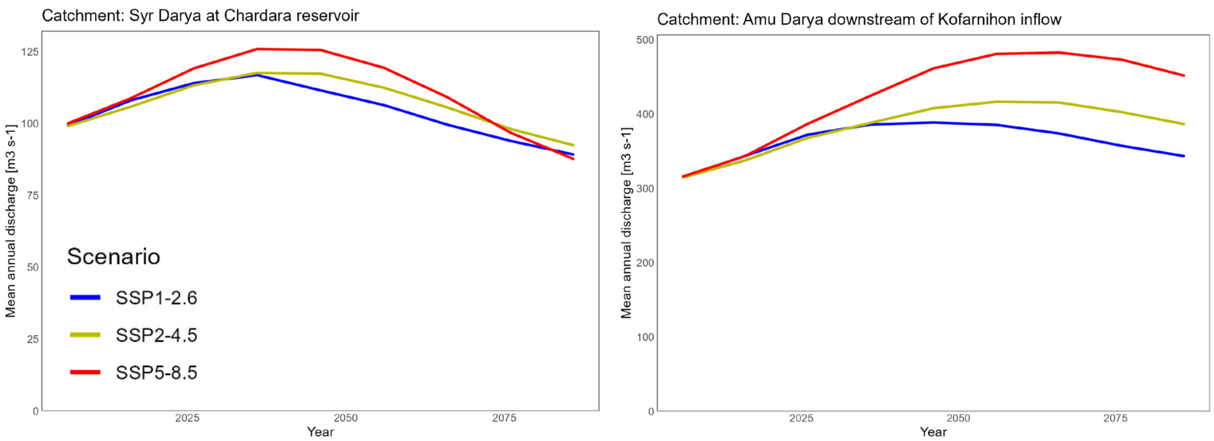

Figure 4.1.1: Annual glacier meltwater contribution to total river runoff for Syr Darya and Amu Darya.

The stark contrast in ice volume changes between the Tien Shan and Pamir basins is mirrored in the glacier meltwater contributions of their sub-basins (Fig. 4.1.1 and Table 4.1.2). The predicted mean annual discharge includes only the glacier contribution to total catchment runoff (see section 2.2). Syr Darya as well as Issyk Kul, Kaskelen, and Chuy, are expected to experience significant reductions in annual glacier meltwater inflow by the end of the century. For example, Chuy, Kaskelen, and Issyk Kul, the most strongly affected catchments, could see up to a 25% reduction in meltwater input. This decrease is not driven by changes in atmospheric warming, but rather by the fact that the ice volume in these catchments will have been depleted to a point where it can no longer sustain the current level of meltwater production. In contrast, the Amu Darya basin, and the Karakul and Zeravshan catchment, are projected to experience an increase in meltwater contribution. Under a low-emission scenario, this increase could be up to 16%, while under a high-emission scenario, highly glaciated catchments, such as the Muksu catchment could see an 80% increase in meltwater input. The Muksu catchment, which hosts the Fedchenko Glacier, is particularly critical to future water availability, with basin-wide meltwater changes largely driven by this glacier's behavior. In the Amu Darya sub-basins, meltwater contributions could increase by up to 35-70%, raising annual glacier meltwater discharge by as much as 1.8 times the rate of 1991–2020. Such a significant increase in meltwater inflow could have dramatic consequences for water availability, potentially causing flooding and inundations as well as affecting hydropower plants.

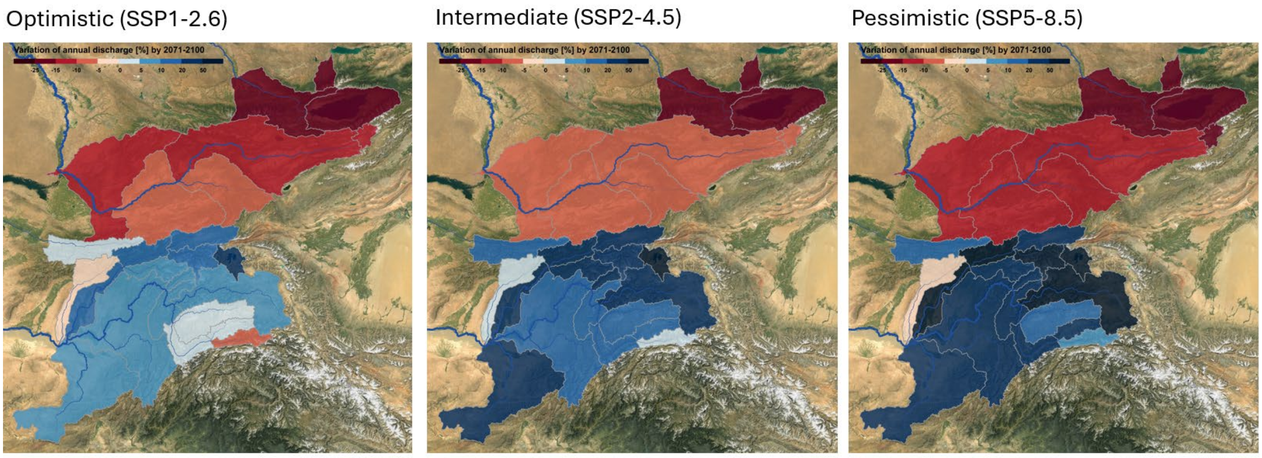

Figure 4.1.2: Relative variation (present-day to 2100) of the glacier meltwater contribution to total annual river runoff by catchment, for the three emissions scenarios.

Table 4.1.1: Changes in annual glacier meltwater contribution to total river runoff for each modelled catchment for different future time periods.

Optimistic (SSP1-2.6)

Watershed	Discharge: 1991-2020	Change in discharge: 2001-2030	Change in discharge: 2031-2060	Change in discharge: 2071-2100
	($m^3 s^{-1}$)			
Amu Darya	315	29	74	29
Bartang	41	4	11	4
Chuy	26	1	-1	-5
Gunt	19	2	5	0
Issykkul	30	2	0	-7
Karadarya	4	0	0	0
Karakul	8	1	4	2
Karasay	14	1	4	-2
Kaskelen	3	0	0	-1
Khingov	47	4	10	4
Kofarnihon	7	0	1	0
Kyzylsu	20	2	6	2
Muksu	79	8	24	13
Naryn	45	5	8	-5
Pamir	8	1	2	0
Panj	134	13	30	8
Syr Darya	99	9	12	-10
Vakhsh	173	16	44	20
Vanchob	17	1	3	15
Wakhan	5	0	1	1
Zeravshan	37	3	5	0

Intermediate (SSP2-4.5)

Watershed	Discharge: 1991-2020	Change in discharge: 2001-2030	Change in discharge: 2031-2060	Change in discharge: 2071-2100
	($m^3 s^{-1}$)			
Amu Darya	314	23	94	72
Bartang	41	3	15	11
Chuy	26	1	0	-5
Gunt	18	2	6	2
Issykkul	30	2	1	-6
Karadarya	4	0	1	0
Karakul	8	1	5	4
Karasay	14	1	5	-1
Kaskelen	3	0	0	-1
Khingov	47	3	13	11
Kofarnihon	7	0	1	0
Kyzylsu	20	2	8	5
Muksu	79	6	27	28
Naryn	45	4	10	-4
Pamir	8	1	3	1
Panj	134	10	41	26
Syr Darya	99	7	18	-7
Vakhsh	173	13	52	46
Vanchob	17	1	4	4
Wakhan	5	0	1	0
Zeravshan	37	2	7	4

Pessimistic (SSP5-8.5)

Watershed	Discharge: 1991-2020	Change in discharge: 2001-2030	Change in discharge: 2031-2060	Change in discharge: 2061-2090
	($m^3 s^{-1}$)			
Amu Darya	316	28	146	136
Bartang	41	4	23	22
Chuy	26	1	1	-6
Gunt	18	2	9	4
Issykkul	30	2	2	-6
Karadarya	4	0	1	0
Karakul	8	1	8	5
Karasay	14	1	7	-3
Kaskelen	3	0	0	-1
Khingov	47	3	18	18
Kofarnihon	7	0	1	0
Kyzylsu	21	2	11	6
Muksu	79	7	45	64
Naryn	45	4	14	-7
Pamir	8	1	4	3
Panj	134	13	61	48
Syr Darya	100	9	26	-12
Vakhsh	174	14	82	89
Vanchob	17	1	6	7
Wakhan	5	0	2	0
Zeravshan	37	3	11	5

4.2 Seasonal changes in meltwater contribution

The contribution of glacial meltwater plays an important role in regulating river flow dynamics, affecting both the timing and volume of discharge in rivers (Fig. 4.2.1). During the melt season, this contribution can increase up to 70-90% for Amu Darya and 20-40% for Syr Darya of the average annual input (Saks et al., 2022; Armstrong et al., 2019, Huss and Hock, 2018). Glacier melt provides a reliable water supply for agriculture, industry and environmental protection, especially after the seasonal snowpack has been depleted. Therefore, understanding the seasonal distribution of water available from glacier melt is at least as important as examining the annual runoff contributions.

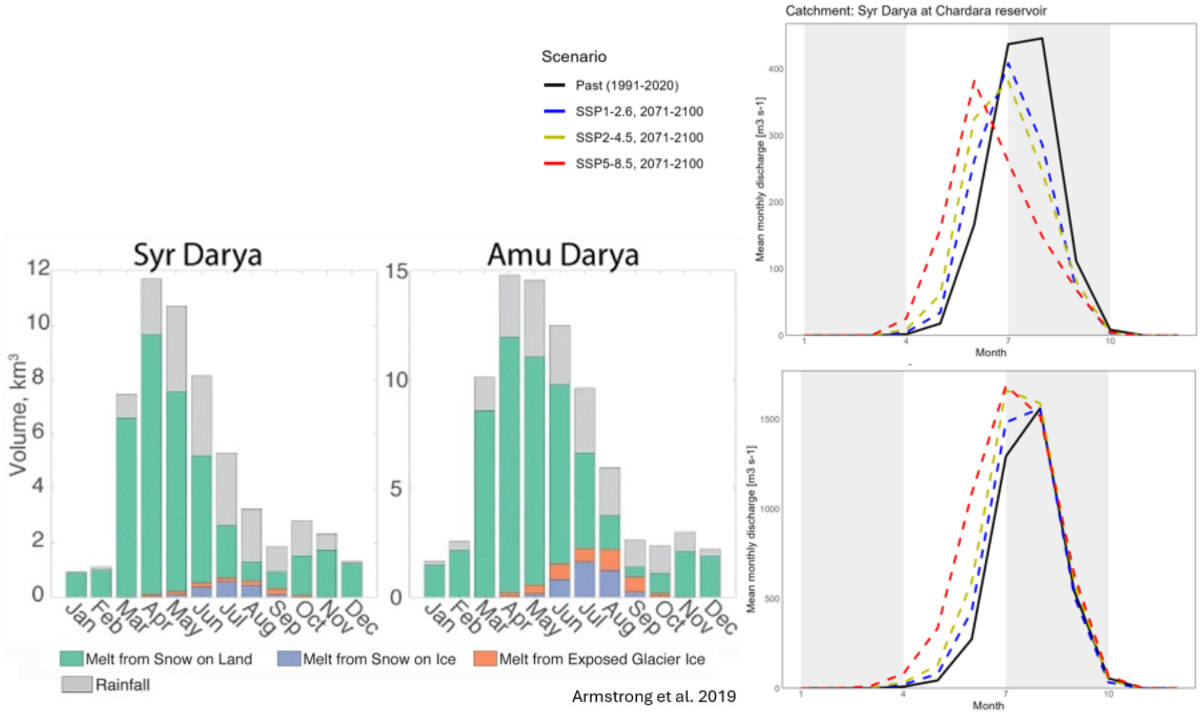

Fig. 4.2.1: Monthly runoff distribution for the different water resource components provided in Armstrong et al., (2019) for Syr Darya and Amu Darya (left). Seasonal glacier meltwater contribution changes for the Syr Darya and Amu Darya catchment in 2100 (right).

In Central Asia, the melt season typically begins in mid to late April and lasts until early October (Fig. 4.2.1 and Fig. S2), whereas in the early season snow on glaciers will contribute mostly to the runoff, while ice melt only starts when the snow line starts to rise on the glacier, typically in late June to the beginning of July. The melt season is slightly shorter in the highest catchments of the Pamir Mountains, where melt typically begins in May (Fig. S2). For most basins, glacier meltwater release peaks in August, except for Syr Darya, Kara Darya, Kaskelen, Zeravashan, and Chuy basins, where meltwater inflow is similar in July and August and for the Kofarnihon, where a pronounced peak occurs in July (Fig. S2). The timing of this peak meltwater contribution will be strongly influenced by future changes in ice extent, as these changes will not be evenly distributed throughout the year.

In the Amu Darya basin, the contribution of meltwater will increase in spring and early summer, while in the Syr Darya basin, the contribution of meltwater is projected to decrease in late summer, accompanied by an overall decrease in seasonal peak discharge (Fig. 4.2.1). In both basins, the melt season is projected to start earlier - as early as late March under all emission scenarios. This will lead to a rapid increase in melt rates, resulting in more excess water flowing into the two major Central Asian rivers in spring.

While atmospheric warming will shift the onset of the melt season earlier in most basins, the Gunt, Panj, Wakhan and Pamir basins (Table 2.1.1 for basin description) are exceptions (Figs. 4.2.1, 4.2.2, 4.2.3, 4.2.4 and S2). The earlier onset of spring ablation is accompanied by a greater increase in meltwater release, resulting in rivers receiving more meltwater in a shorter period of time (Fig. S2). This accelerated spring and early summer melt will shift the peak glacier meltwater contribution from August to a more evenly distributed July-August peak or even a July maximum, especially under high and intermediate emission scenarios. Only a few basins, such as Vakhsh, Muksu and Karakul, are expected to maintain their peak meltwater contribution in August (Fig. 4.2.3). In contrast, basins such as Kofarnihon, Chuy, and Kaskelen will shift their peak meltwater contribution as early as June (Fig. 4.2.2).

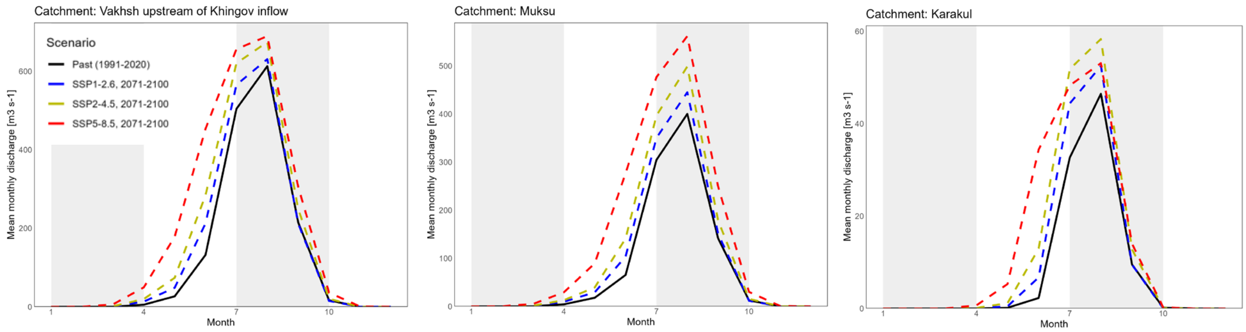

Fig. 4.2.2: Seasonal glacier meltwater contribution changes for the Chuy, Kaskelen and Issyk Kul catchment in 2100.

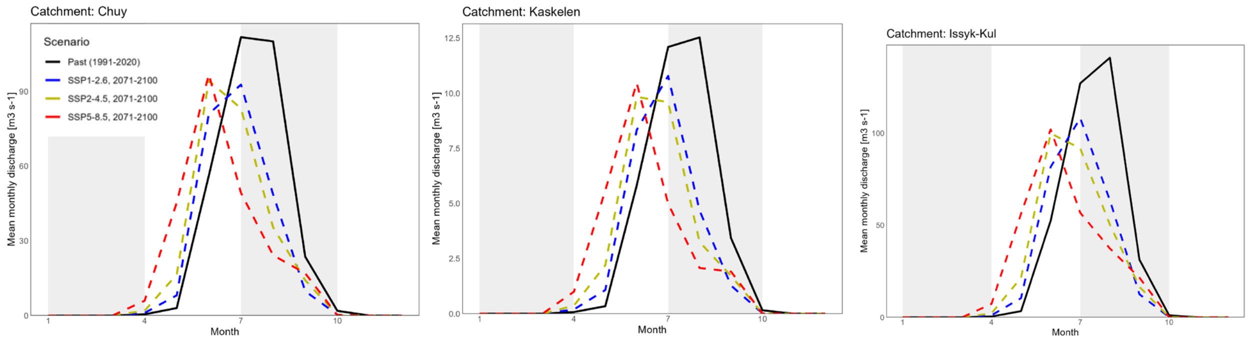

Fig. 4.2.3: Seasonal glacier meltwater contribution changes for Muksu, Vaskhsh and Karakul catchment in 2100.

Long-term runoff observations highlight the ongoing changes in the Naryn catchment. Runoff has increased in the summer months from 1940 to 2000 due to accelerated melting in a warming climate (Fig. 4.2.4). While the peak runoff for this period remained in July, a shift over the last 20 years towards an earlier maximum runoff indicates that peak water for this catchment will be reached very soon and that summer runoff will decrease within the next few decades (Fig. S1). By the end of the century, the peak meltwater contribution will occur before the onset of the hot and dry summer period, and a substantial portion of the summer meltwater contribution will be lost. This may be as low as less than 50% of the current runoff under an extreme emissions scenario (Fig. 4.2.4).

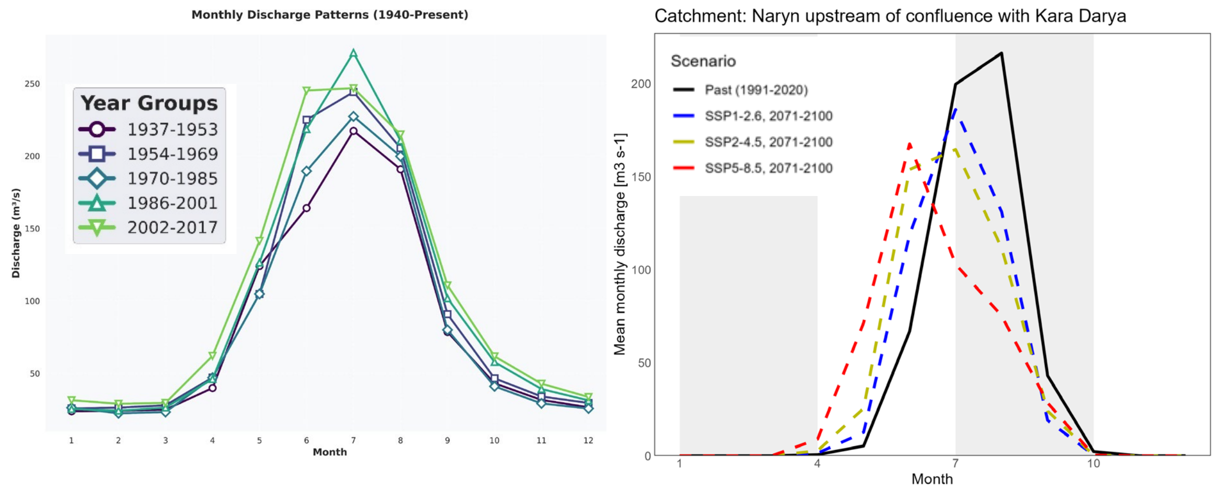

Fig. 4.2.4: Historical seasonal runoff change (left, Saks et al., 2022) and predicted changes in 2100 for the Naryn catchment under the three emission scenarios (right).

While meltwater contributions during the early summer months will continue to increase in most Pamir catchments (such as the Amu Darya, Panj, Vanchob, Bartang, Gunt, Khingov, Vakhsh, Muksu and Karakul), catchments in the Tien Shan will experience significant reductions in the magnitude of the peaks and summer meltwater contributions. These reductions will have a major impact on total river discharge, as glaciers in the Tien Shan contribute about 42% of the freshwater input to Syr Darya (Huss and Hock, 2018). The strongest reductions for summer are predicted for the Chuy, Kaskelen, Issyk-Kul, Naryn and Karasay basins, which contain some of the most densely populated areas in the region (Fig. 4.2.3). In the Pamir, Kofarnihon, Gunt, Kyzylsu and Wakhan are expected to experience a decrease in summer meltwater by 2100, with the latter two being the only Pamir basins projected to experience a decrease in meltwater contribution from current levels by the end of the century. Vakhsh and Muksu, on the other hand, are projected to have increasing meltwater contributions during all months under all scenarios, and Karakul is projected to experience a strong increase from June to August (Figure 4.2.4).

Some of the most significant changes in meltwater contributions are expected in May and August (Fig. 4.2.5, S3, S4). For May, almost all catchments show an increase in meltwater contribution under all scenarios, highlighting the prolonged melt season. This shift is driven by higher temperatures at higher elevations, leading to earlier melting of snow, ice and firn, with meltwater release potentially two to three times higher than current levels. Snowmelt as well as glacier melt will both increase in early spring and therefore will fill up rivers faster leading to reduced seasonal and multi-annual storage capacity of the basins. In larger basins, such as the Syr Darya and Amu Darya (Figure 4.2.1), the contribution of early spring glacier meltwater is relatively small compared to snowmelt, which remains the most important source of water for spring. In these basins, the importance of rain will increase and partly compensate for a change in snow and glacier melt inflow on an annual scale in a warmer climate. However, the combined effect of increased and earlier glacier melt and increased rainfall could overwhelm the river systems and increase the likelihood of spring flooding and mudflows.

In contrast, meltwater inflow in August is projected to decrease dramatically for the Tien Shan catchments, with reductions of 60-80% under intermediate emission scenarios, and almost complete meltwater loss for many Tien Shan catchments under high emission scenarios, leaving the region dry in late summer (Fig. 4.2.5). While catchments in the Pamir may not experience substantial reductions in peak flows, the shift to earlier meltwater contributions will make river basins such as Zeravshan, Kyzylsu, Gunt, Panj, Wakhan, Pamir and Kofarnihon drier in August under the optimistic scenario, other basins such as Panj, Vanchob and Khingov will add to this with similar reductions under higher emission scenarios (Fig. 4.2.5).

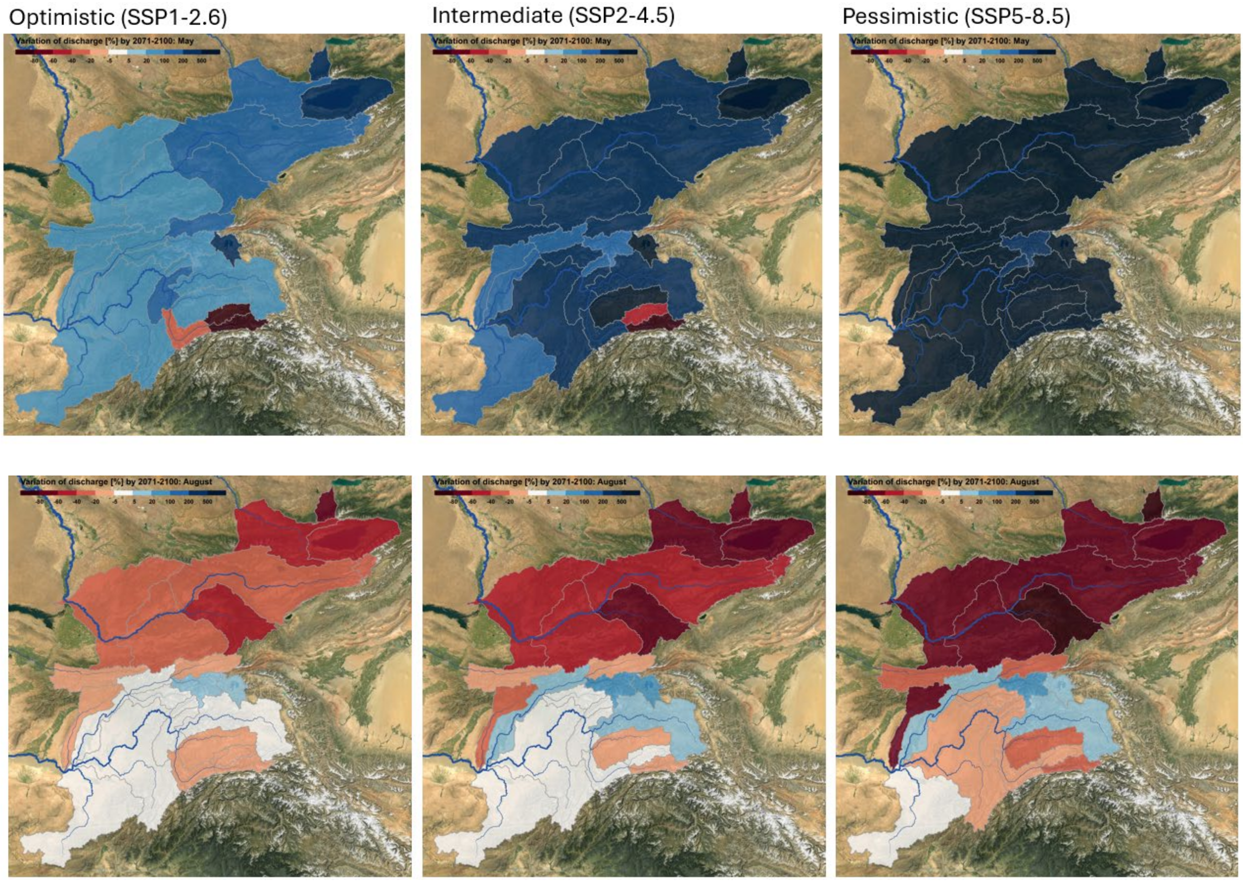

Fig. 4.2.5: Glacier meltwater change for each catchment by the end of the century under the three emission scenarios for May (top) and August (bottom).

CHAPTER 5: DISCUSSION

5.1 Runoff contribution changes

For Central Asia, hydrological model projections in Siegfried et al. (2024) indicate increases in actual evaporation between 7% and 17% and changes in runoff between +1% and -3% for the SSP1-2.6 and SSP5-8.5 scenarios, respectively. Under the most extreme climate scenario (SSP5-8.5), runoff increases of 3.8% and 5.0% are expected in the first and second future periods, followed by a decrease of -2.7% in the third period. The projected increases and decreases for the catchments over time are consistent with the predicted increase in glacier meltwater contribution patterns. Siegfried et al. (2024) highlight the diverse hydrological responses to climate change in the high mountains of Central Asia. Different mechanisms in sub-basins and between altitudinal zones lead to geographically different climate impacts in the twenty-first century. The authors highlight the importance of the glacier meltwater contribution, which is consistent with our results (Fig. 5.1.1).

Siegfried et al. (2024) conclude that the Tien Shan will experience drying out of the runoff formation zone as glacier ablation accelerates and glacier ice is lost during the 21st century (Fig. 5.1.1 and Fig. 5.1.2).). The rivers originating in Pamir Mountains will experience an increase in runoff throughout the 21st century, in part due to increased glacier melt and the fact that peak runoff occurs later there, as well as to some extent probably due to projected increased precipitation rates (Fig. 3.1.2).

In all areas of significant glaciation, increased glacier ablation stabilizes total river discharge until peak glacier meltwater occurs (Siegfried et al., 2024). The authors also emphasise the importance of the timing of peak water in stabilizing river discharge and do not expect a significant change in water availability in the Syr Darya basin, despite the large reduction in the contribution of glacier meltwater in the basin. This contrasts with the Chuy and Issyk Kul basins, where total river discharge will decrease. An increase in discharge variability is also expected for the region. The increased frequency of high discharge events also raises concerns about flood risks, necessitating the development of more robust flood mitigation strategies. Similarly, Barandun et al. (2021) found higher variability in annual glacier mass balance, highlighting the risk of extremely high to low glacier meltwater contributions. This could pose challenges for water management, as infrastructure and agricultural practices may need help to adapt to more erratic water availability and extreme flows. One of the biggest risks is high spring temperatures, which can lead to increased snow and glacier melt, combined with high precipitation events, and may become more frequent in the future.

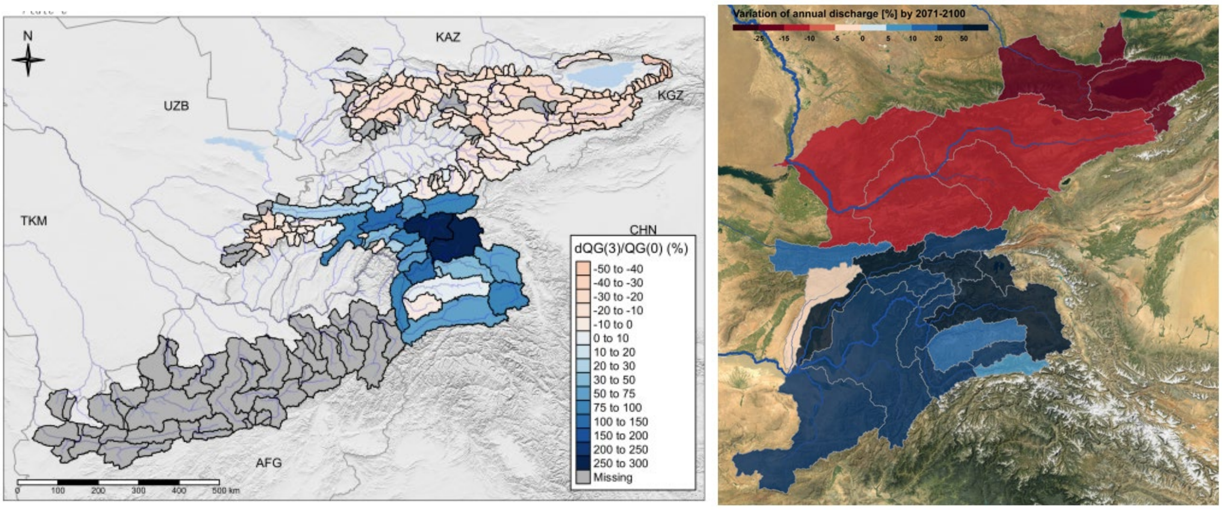

Figure 5.1.1: Annual glacier meltwater contribution to total river runoff provided in Siegfried et al. (2024) and from our study by 2100 for the most high-emission scenarios (SSP5-8.5).

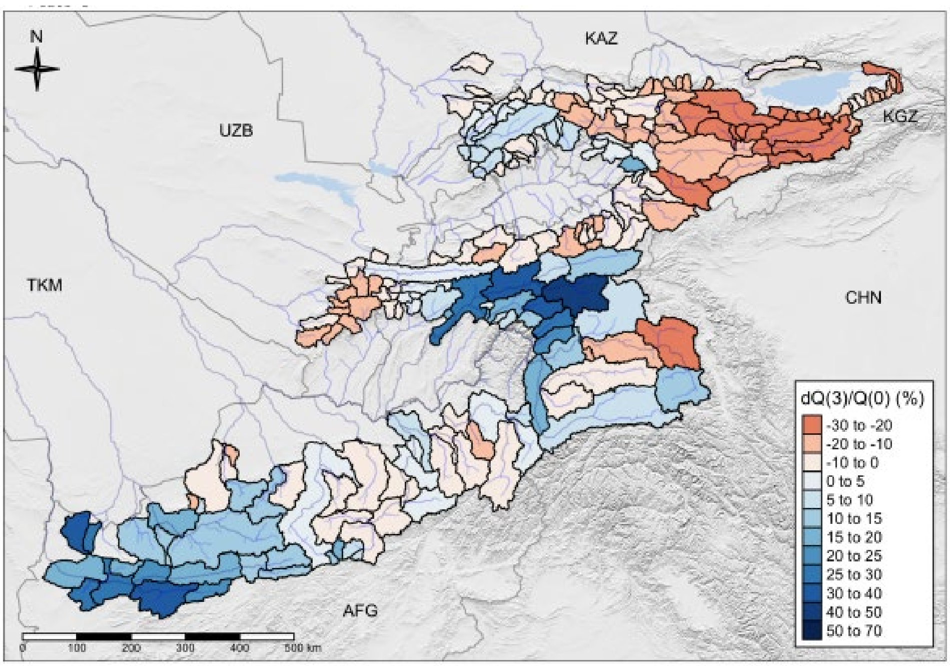

Figure 5.1.2: Projected total river discharge change provided in Siegfried et al. (2024) until 2100 for the most high-emission scenarios (SSP5-8.5). Discharge is based on modeling of the entire water balance and includes contributions from rain, snow, groundwater, and glacier melt as well as evaporation.

5.2 Changing Water Resources under Climate Change

In Central Asia water withdrawal closely matches availability (IPCC AR6). Turkmenistan and Uzbekistan are the most water-stressed countries in the region (Karthe et al., 2017; Russell, 2018; FAO-AQUASTAT, 2021), with 88% of Turkmenistan's surface water originating from the Amu Darya, flowing outside its borders into Tajikistan and Afghanistan (Nationally Determined Contribution of Turkmenistan under the Paris Agreement, 2022; Duan et al., 2019). The cumulative effects of climate change will be profound and aggravate the pressure on water resource management. The climate of Central Asia is strongly continental. In the south and east, the mountain ranges of the Himalayas, Pamir, Hindu Kush and Tien Shan almost completely isolate Central Asia from humid air masses from the Indian Ocean. Because of these barrier effects, large parts of the Tien Shan and Pamir are dominated by dry and cold conditions. For the Tien Shan, a steady increase in air temperature of about 0.1 to 0.2°C per decade was recorded during 1960-2007, with more pronounced warming in the winter months. For the Pamir, the temperature increased from 0.07 to 0.11°C yr^{-1} for the same period (Barandun et al., 2020).

Warming in Central Asia is expected to exceed the global average, with temperatures rising by an average of 5-6°C by 2100 (Sara J. & Proskuryakova T., 2022). Ice and snowmelt are the main water resources for the densely populated lowlands of Central Asia (Konovalov & Shchetinnicov, 1994; Schaner et al., 2012; Chen et al., 2016) and play a crucial role for mountain communities (Figure 2.2.1; Nüsser, 2017; Nüsser et al., 2019; Sitara et al., 2015). Snow accumulation acts as a water reservoir, especially during the winter months, and controls streamflow in the spring and early summer. Glacier meltwater contribution on the other hand is more important in summer. Currently, the annual contribution of glacial meltwater from the Tien Shan Mountains to the upstream flow of the Syr Darya is 2% per year. The contribution of glacial meltwater to the Amu Darya is about 8% per year (Amstrong et al., 2019, Huss and Hock, 2018). Under the different emission scenarios, glacier meltwater contribution will decrease for Syr Darya and increase for Amu Darya until the end of the century. More important however is the change in seasonal distribution. Most meltwater will become available in early spring while for Syr Darya the total amount of meltwater inflow will decrease and for Amu Darya it will still increase.

Consequently, based on climate projections, both extreme floods and extreme droughts will increase. This implies changes in the seasonality of the snowpack, resulting in earlier melting that could lead to more spring and summer runoff in low snow years or droughts (Siegfried et al., 2012, 2024). Increased runoff has the potential to trigger Glacier Outburst Floods (GLOFs) events, debris flows and landslides threatening mountain settlements.

Central Asia faces significant water challenges due to shared water resources, uneven distribution, and increasing competition between users (Munia et al., 2016; Krasznai et al., 2019). The region's growing population has driven up water demand, exacerbating these challenges (Mankin et al., 2015). Water resource management remains fragmented across multiple ministries, and despite ongoing legal reforms, implementation has been hindered by gaps in national strategies, weak monitoring systems, and insufficient capacity and coordination (Cassara et al., 2019). Inappropriate use of fertilizers and pesticides has worsened water quality, leading to soil salinization and contamination (Cassara et al., 2019; Bekturganov et al., 2016).

The depletion of water resources from the Amu Darya and Syr Darya rivers, caused by excessive water use for irrigation, has contributed to environmental disaster of the Aral Sea dessication by 2014 (Dukhovny & Schutter, 2011). Despite the shrinking role of agriculture in the region's GDP since the Soviet Union (Hamidov et al., 2016), the demand for water remains high, especially for irrigation. These water supply challenges, combined with rapid industrialization, are heightening the risk of water scarcity, particularly during frequent droughts that affect crop yields and contribute to soil erosion and degradation (Idrisov, 2023).

Sustainable Development Goal (SDG) 6.4.2 Indicator of Water stress assesses the level of water stress, meaning how intensively freshwater is used compared to the available resources in countries. The indicator shows how much water is withdrawn in relation to the total freshwater available, taking into account that some water is needed by nature to maintain ecosystems. When the water stress level is >=100%, it means that the entire available water volume (after accounting for ecosystem needs) is used for human needs, indicating a high level of stress and risk of water scarcity. If the water stress level is low (close to zero), it means that the amount of water withdrawn is a small fraction of the total stock, and water stress in this case is minimal. The SDG 6.4.2 target is to reduce the Water Stress in countries to the level <=25% by 2030.

The Table 5.2.1 shows the level of water stress in the Central Asian countries and shows that Turkmenistan and Uzbekistan are under high stress, using all available water resources downstream of the Syr Darya and Amu Darya river basins mainly for agriculture, industry and municipalities rather than for ecosystems.

The socio-economic development of Central Asian countries is closely linked to the availability of water resources (Abdullaev et al., 2019), which highlights the importance of water use efficiency for economic growth. Water Use Efficiency, measured by the SDG 6.4.1 indicator, shows how much economic value is generated from each cubic meter of water used in three main sectors: (a) agriculture, forestry, and fishing; (b) mining, manufacturing, energy production, and construction; and (c) services. This indicator helps to understand how efficiently water resources are used to produce economic benefits. Low efficiency values show high water losses and poor management in these sectors. As water demand rises and climate change makes water systems more vulnerable, improving water use efficiency is crucial to ensure food security and support sustainable economic growth in the region.

Table 5.2.1: SDG 6.4.2 Water Stress Indicator in Central Asian countries as of 2021 (Made by author based on FAO AQUASTAT)

Country	**Water stress indicator as of 2021 (SDG 6.4.2)**
Kazakhstan	34.1%
Kyrgyzstan	50.04%
Tajikistan	69.94%
Turkmenistan	135.21%
Uzbekistan	121.84%

In Central Asia, the average Water Use Efficiency is 3.49 USD per cubic meter (FAO AQUASTAT, 2021). This means that, on average, each cubic meter of water used brings 3.49 USD to the region's economy. However, the numbers vary widely across countries: Kazakhstan reaches 8 USD/m^3, while Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan have lower values of 0.88 USD/m^3, 1.08 USD/m^3, 2.03 USD/m^3, and 2.53 USD/m^3, respectively. In comparison, the global average is 20.77 USD/m^3, with Switzerland achieving an impressive 611.43 USD/m^3.

Improving this indicator requires reducing water losses in irrigation, adopting more efficient irrigation methods like drip irrigation, focusing on less water-demanding crops, and improving overall water management. In comparison with the Climate Change impact on the cryosphere and water resources, these steps are essential to boost the economic value of water and ensure its sustainable use in the context of increasing water stress. Central Asian countries are among the highest per capita water users in the world (Dukhovny & Schutter, 2011). Table 5.2.2 shows the water consumption per capita in Central Asian countries. The average water withdrawal per capita per year in Central Asia is 1'359.28 m3/inhab/year, in comparison with the overall world level of water withdrawal per capita per year 504,09 m3/inhab/year.

Table 5.2.3: Total water withdrawal per capita in Central Asia (Made by author based on FAO AQUASTAT)

Country	Total water withdrawal per capita (m3/inhab/year)				
	2017	2018	2019	2020	2021
Kazakhstan	1 335.04	1 269.93	1 260.30	1 294.26	1 279.61
Kyrgyzstan	1 251.38	1 230.82	1 211.33	1 192.24	1 173.45
Tajikistan	894.96	1 070.76	1 135.48	1 037.39	1 015.38
Turkmenistan	4 834.84	4 431.94	4 499.22	4 198.86	2 740.50
Uzbekistan	1 843.75	1 739.25	1 636.78	1 527.62	1 281.11

According to FAO AQUASTAT data, the total population of Central Asian countries has increased from 71.3 million in 2017 to 75.9 million in 2021, reflecting an average annual growth of approximately 1 million people across the region. Based on this trend, the projected population for Central Asia is estimated to reach 95 million by 2040, 115 million by 2060, 135 million by 2080, and 155 million by 2100. On the other hand, over the past five years, the average annual water consumption per capita in the region has been decreasing by approximately 108.63 cubic meters per year.

This demographic growth significantly increases total water demand, even if per capita water consumption remains constant. However, the current per capita consumption rate is insufficient to meet the rising water demands. Coupled with hydrological changes, including the decreasing contribution of glaciers and snowmelt to river runoff, the region faces mounting water scarcity and stress. Addressing these challenges requires urgent measures to reduce per capita water consumption and improve water use efficiency by minimizing losses.

The cumulative effects of climate change in Central Asia are expected to be profound, with warmer temperatures causing earlier snowmelt, increasing water demand, and shortening the irrigation season. These changes, combined with alterations in cryosphere meltwater contribution, will likely lead to more extreme floods, droughts, and overall water scarcity (Sara & Proskuryakova, 2022). The unregulated use of water, particularly for agricultural irrigation, and its impact on hydropower generation (Schrader et al.,

2019) are additional threats to the region. Water reservoir levels, essential for electricity production and summer irrigation, are also declining due to ongoing climate change. Existing challenges, such as fragmentation of water resource management, gaps in regulatory frameworks, and insufficient attention to environmental and health issues, place additional stress on water resources management in the countries. The region faces increasing water demand due to population growth and economic development, leading to water insecurity in the region.

CHAPTER 6: CONCLUDING REMARKS

The arid zone of Central Asia constitutes a region confronted with a complex interplay of environmental, social, and economic challenges. The countries heavily rely on the shared water resources of the Amu Darya and Syr Darya river basins, the majority of which are fed by snow and glacier melt, making the cryosphere a crucial component of the region's water supply.

Over the rest of the 21st century, glaciers in the mountain ranges of Central Asia are expected to continue the current, accelerating trend of mass losses . According to the analyzed results from the Global Glacier Evolution Model (GloGEM; Huss&Hock, 2015; Bosson et al., 2023) a total ice volume loss of 58-85% by 2100 is estimated, depending on the climate scenario. While in the Pamir, the highest and thickest glaciers survive the century, many regions in the Tien Shan and lower elevation basins in the Pamir experience pronounced ice volume retreat to complete deglaciation until the end of the century.

Rapid glacier change will affect the hydrological regime of mountain catchments. Annual runoff is expected to reach a maximum (due to increased melt) for some of the Tien Shan catchments within the next years to a decade, followed by a decrease as glaciers retreat. The timing of such peak water occurrence is controlled by the present-day amounts of ice (both in absolute terms and relative to the catchment area) and thus catchments in the Pamir will reach peak water later. While the peak is expected after the year 2100 for the largest glacier complexes in the Pamir, smaller catchments with more modest glacierization may already be past maximum runoff. Within the seasonal cycle, by 2100 runoff from glaciers is projected to strongly decrease in the late melt season (August to October) for the Tien Shan, by more than 30% of the corresponding total basin runoff. On the contrary for the Pamir, runoff contribution during the summer will not decrease substantially but shift to earlier time periods in the season.

All projections of future glacier change come with significant uncertainties, linked to the incomplete knowledge of the climatic and non-climatic drivers of glacier mass balance and the complex process chains and feedback effects driving glacier evolution in the different sub-regions (Barandun et al., 2020). Specific challenges include an accurate simulation of the evolving glacier debris cover (Compagno et al., 2022) and a better understanding of the future of unstable and non-linear responding glaciers under a changing climate (Kääb et al., 2023). Better constraining the future climate forcing is also an important priority: currently, gridded datasets of even the past climate show severe discrepancies across Central Asia, and largely lack validation data in terms of precipitation intensities and seasonality (Schöne et al., 2019; Zandler et al., 2019). Particularly important for future impact studies are sub-regional and catchment scale assessments of glacier mass changes and their driving processes, as well as their corresponding uncertainties – by combining in situ observations with remote sensing and numerical models (Barandun et al., 2020).

The need to adapt to a changing climate, and ultimately to mitigate climate change requires more accurate information on the interaction between atmosphere, ocean and land, in order to improve our understanding of the major climate cycles of carbon, water and energy.

For the development of National Action Plans for adaptation to the climate change impact on cryosphere and water resources management, the current scenario of the contribution of glacier meltwater runoff should be contrasted with the current development trends of Central Asian countries. These trends show the population growth in Central Asian countries, which, according to statistical data, could double by 2100. On the other hand, the current efforts of the countries to improve the efficiency of water resources use and reduction of the per capita water withdrawal are not sufficient compared to the population growth and economic development, which require more water.

These development indicators, such as water withdrawal per capita, share of agriculture in GDP production per country, water volume per unit of GDP, should be used as leverage for the development of national action plans in order to have a greater impact on the adjustment of the development path of the Central Asian countries. These actions, which aim to reduce the pressure on water resources in economic development, will strengthen the adaptation of Central Asian countries to future changes in water availability through scientifically sound, reasonable and effective measures, and accelerate the achievement of SDG 6 targets at the national and regional levels, thereby strengthening water security.

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ANNEX

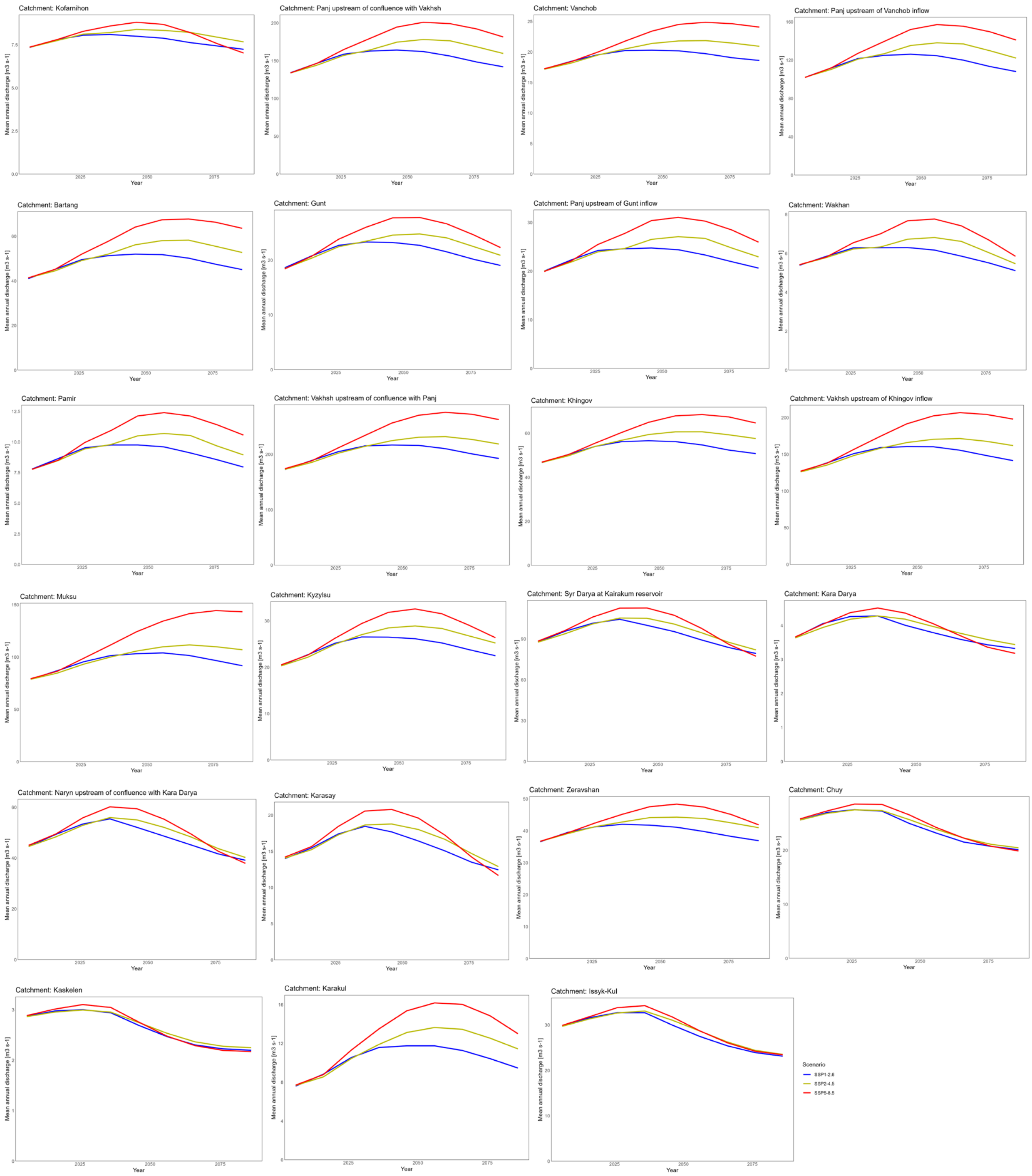

Fig. S1: Annual glacier meltwater contribution projection from 2000 to 2100 for each catchment modelled and all three emission' scenarios.

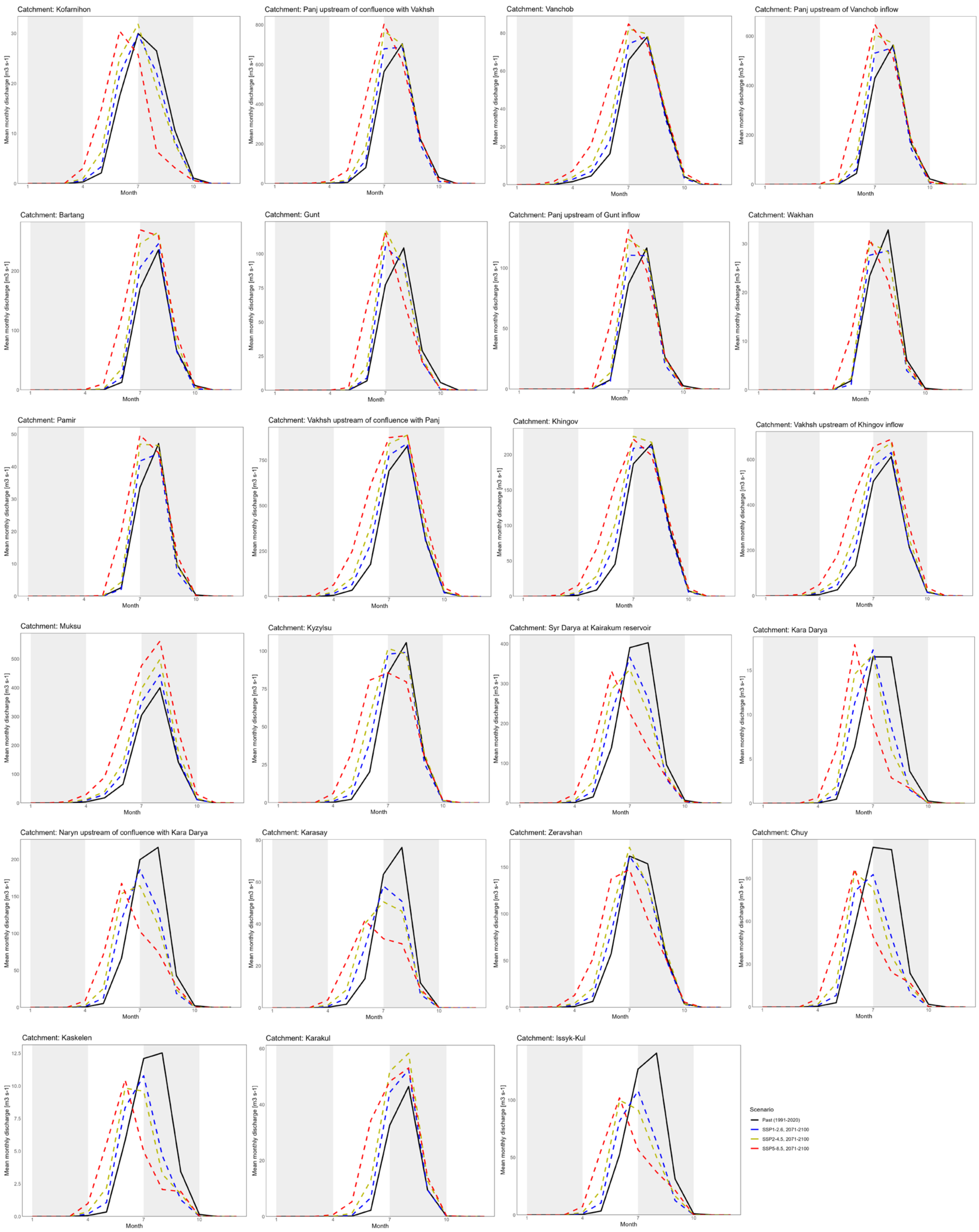

Fig. S2: Seasonal glacier meltwater contribution projection from for 2100 for catchment modelled and all three emission’ scenarios.

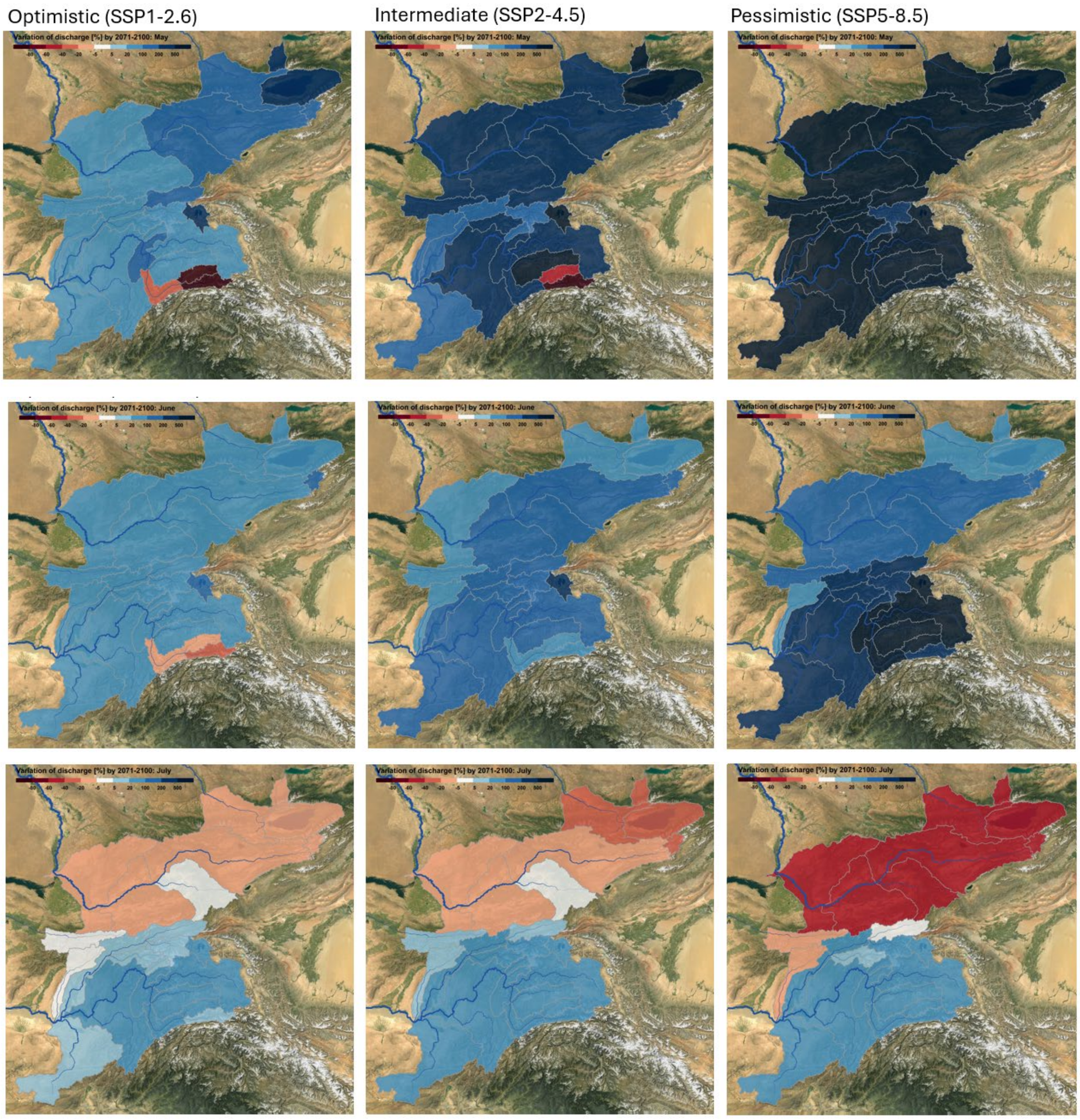

Fig. S3: Relative variation (present-day to 2100) of the glacier meltwater contribution to total annual river runoff by catchment, for the three emissions scenarios for scenarios for August (top), September (middle) and Octobre (bottom).

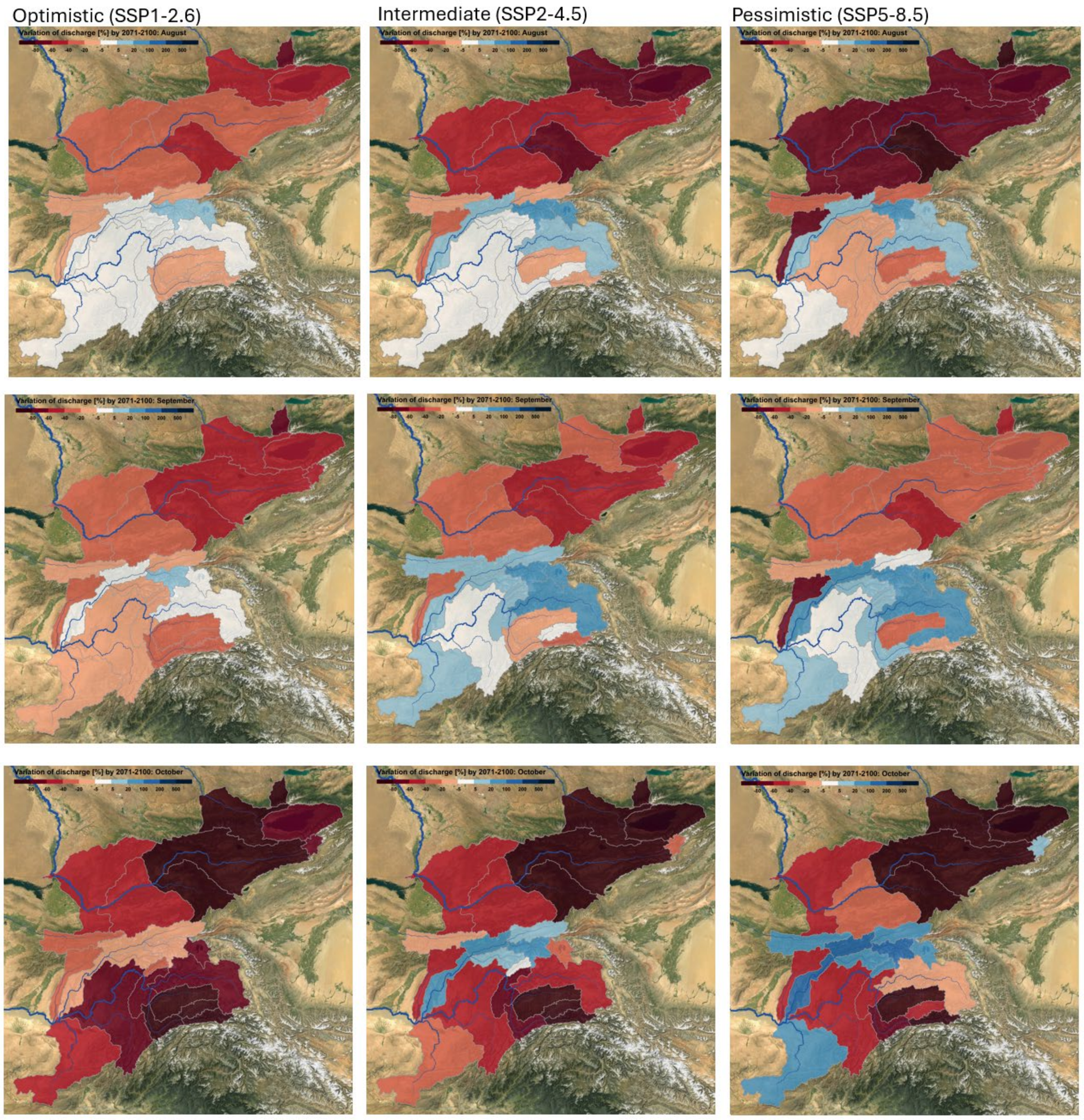

Fig. S4: Relative variation (present-day to 2100) of the glacier meltwater contribution to total annual river runoff by catchment, for the three emissions scenarios for scenarios for August (top), September (middle) and Octobre (bottom).

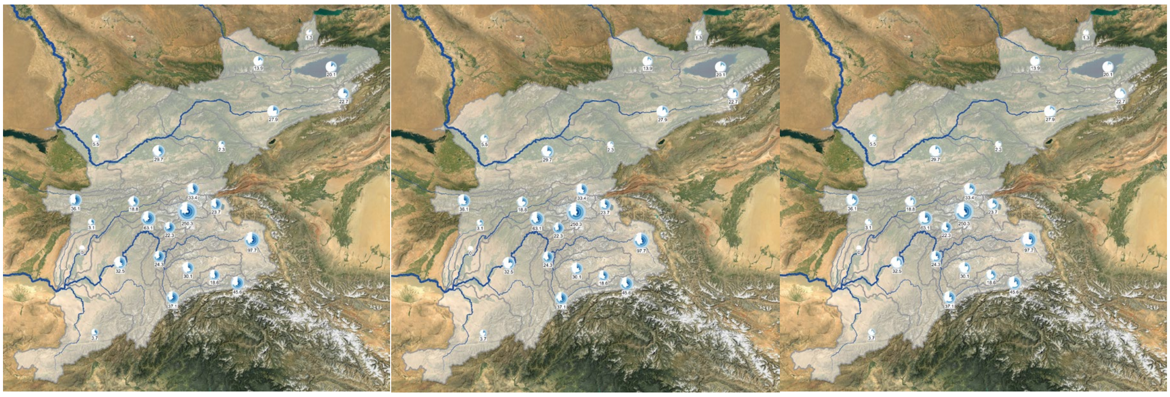

Figure S5: Catchment-wide volume loss for all scenarios. The blue colour in the pie charts indicates the volume change by 2040, 2060, 2080 and 2100 (from lightest to darkest blue) relative to the ice volume in 2020 (numbers below the pie chart).