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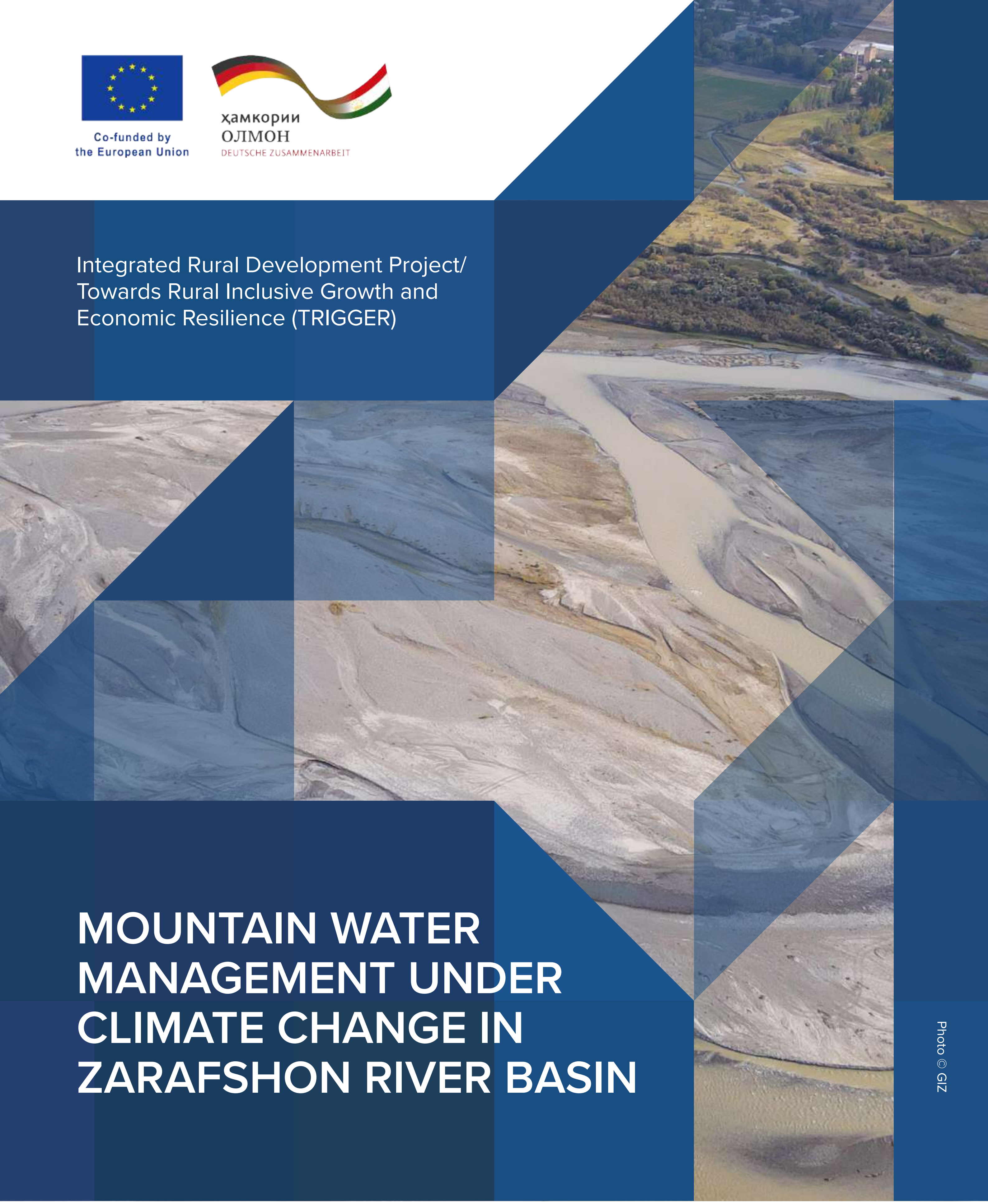

Integrated Rural Development Project/
Towards Rural Inclusive Growth and
Economic Resilience (TRIGGER)

MOUNTAIN WATER MANAGEMENT UNDER CLIMATE CHANGE IN ZARAFSHON RIVER BASIN

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FutureWater

Utrecht University

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Mountain Water Management under climate change in Zarafshon River Basin

Project, funding and partners' contributions

The Integrated Rural Development Project / TRIGGER, co-funded by the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, supports the Ministry of Energy and Water Resources of Tajikistan to strengthen the enabling environment for Integrated Water Resources Management, by improving its capacities for water allocation and formulation of a climate-sensitive river basin management plan for Zarafshon river basin zone, jointly with Zarafshon River Basin Organization and Council.

To this purpose, the Integrated Rural Development Project / TRIGGER mobilized international expertise from the private sector and academia by engaging a Consortium of development partners led by Dutch company Future Water and including the University of Utrecht and the University of Fribourg. The GFA Consulting Group and Helvetas Tajikistan provided fundamental operational and logistical arrangements for the realization of the field interventions that were necessary to achieve the results described in this report.

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ABBREVIATIONS

BMZ	German Federal Ministry for Economic Cooperation and Development
CGR	Center for Glacier Research under the Academy of Sciences of Tajikistan
CMIP6	Coupled Model Intercomparison Projects phase 6
DDFDG	Degree day factor for debris covered glaciers
DDFG	Degree day factor for clean glaciers
DDFS	Degree day factor for snow
DEM	Digital Elevation Model
EoC	End of century
ESA CCI	European Space Agency Climate Change Initiative
GCM	Global Climate Model
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GoT	Government of the Republic of Tajikistan
HMA	High mountains of Asia
IRDP	Integrated Rural Development Project
IWP	Institute of Water Problems, Hydropower and Ecology under the Academy of Sciences of Tajikistan
IWRM	Integrated Water Resources Management
LAI	Leaf-Area Index
MC	Mid-century
MCM	Million Cubic Meters
MCM/y	Million Cubic Meters per year
MDBs	Multilateral Development Banks
MEWR	Ministry of Energy and Water Resources
NDVI	Normalized Difference Vegetation Index
NWIS	National Water Information System
ZRBMP	Zarafshon River Basin Management Plan
RDP II	Rural Development Programme II
SMB	Surface Mass Balance
SPHY	Spatial Processes in Hydrology
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
TAU	Tajik Agrarian University
THA	Tajik Agency of Meteorology
TRIGGER	Towards Rural Inclusive Growth and Economic Resilience
WEAP GUI	WEAP Graphical User Interface
ZRB	Zarafshon River Basin
Zarafshon RBO	Water Resources Department of Zarafshon River Basin

SUMMARY

Climate change

Climate projections for the Zarafshon River Basin (ZRB) in Tajikistan indicate **a warmer future**, with basin-aggregated temperatures expected to reach ~3.75°C under SSP126 and ~9°C under SSP585 by the end of the century (Figure S1). **Precipitation trends show larger variability**, with some models projecting declines of 3–5% and others predicting increases up to 23% by the end of the century horizon compared to the reference, reflecting both seasonal variability and model differences.

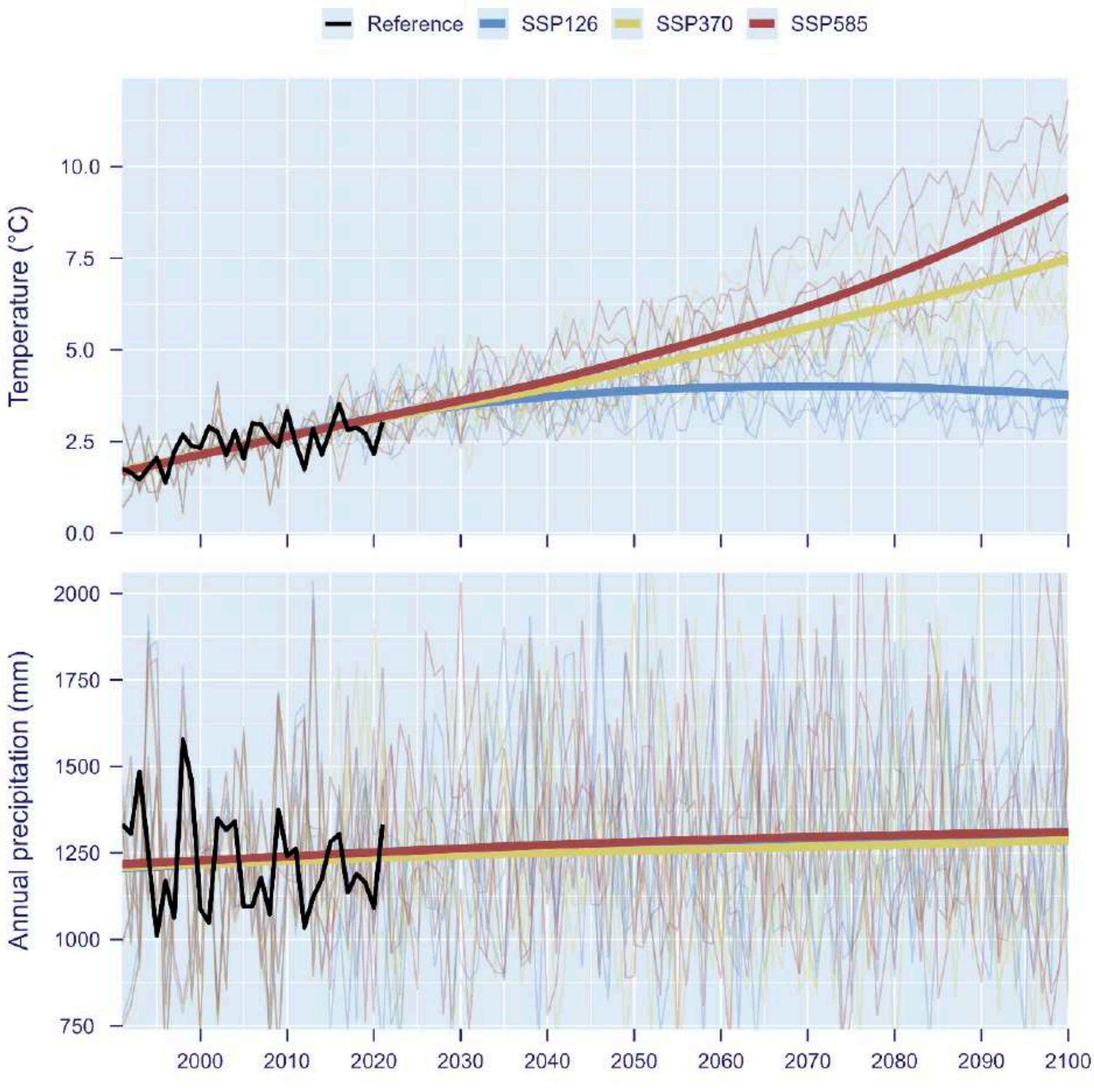


Figure S1: Zarafshon River Basin aggregated downscaled future annual temperature and precipitation timeseries and trends for SSP126, SSP370 and SSP585 scenarios.

Glacio-hydrological modelling of Zarafshon River Basin

The Spatial Processes in Hydrology model (SPHY) is used to understand the baseline and future hydrological regime, flow contributions, spatial differences in flow contributors, and water balance components in the ZRB. The analysis is based on the natural flow modelled by the SPHY model, excluding water infrastructure and human water abstractions. The baseline analysis, using the ZRB-SPHY model (1991–2020), shows that **snowmelt runoff is the dominant contributor (53%)** to total runoff, followed by baseflow (23.1%) and rainfall-runoff (21.3%). The spatial distribution of runoff indicates that snow and glacier melt are more significant in the upstream regions, while baseflow dominates in the lower basin. The hydrological regime shows considerable annual variability due to changes in precipitation, temperature, and snow and glacier reserves, with the highest peak discharge observed in July 2003, corresponding with flooding events. Over the past 30 years, there has been a decline in runoff components, particularly snow and glacier melt, attributed to rising temperatures.

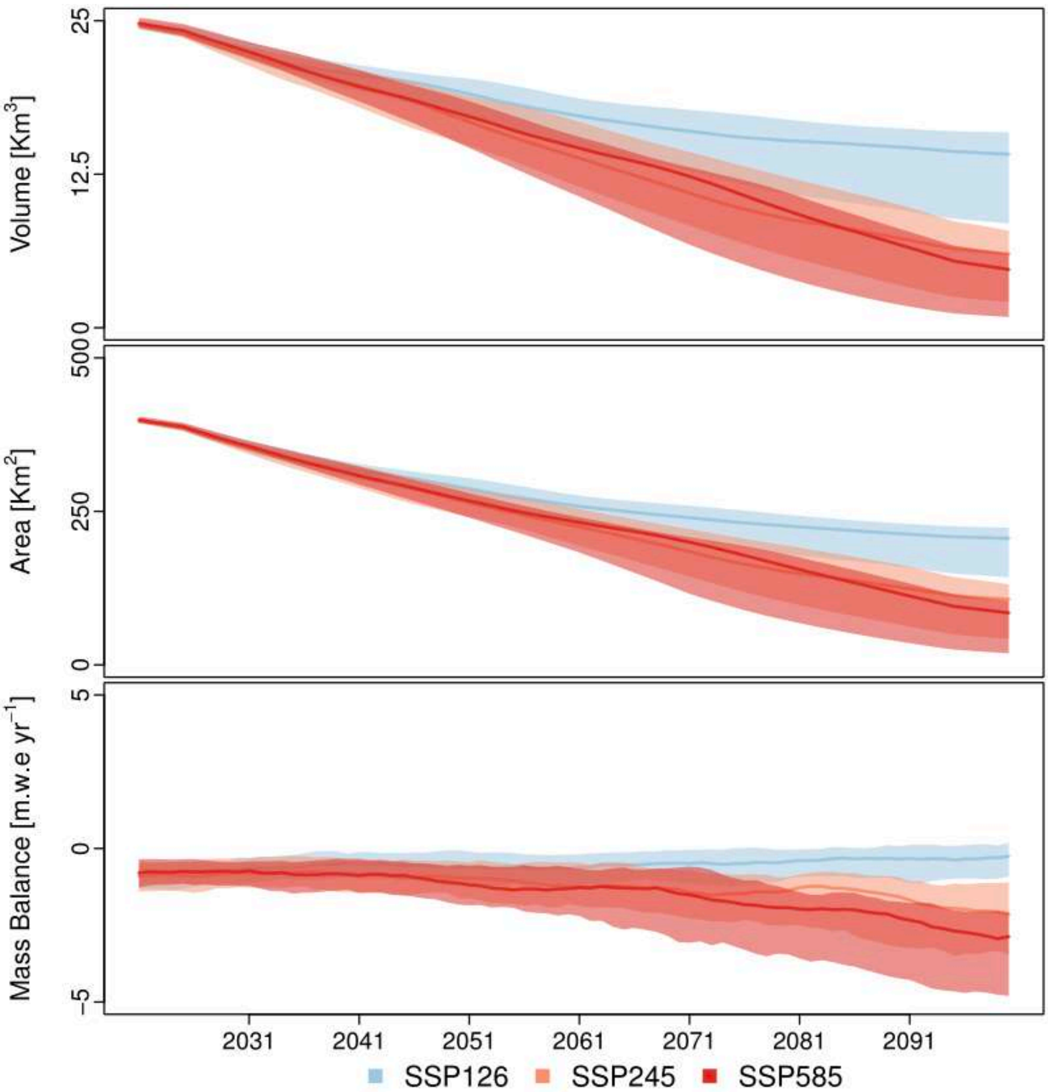


Figure S2: Long-term changes in the total volume (top), area (middle), and mass balance of all the glaciers in the ZRB (just before the Zarafshon River enters Uzbekistan). The shaded color represents the three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585. The bandwidth represents the variability (minimum and maximum) of the five climate models with each SSP. The solid-colored line represents the median of the five climate models.

Future climate change impacts on the cryosphere indicate that glaciers in the ZRB will experience rapid volume and area decline under all SSP scenarios, with the most significant reductions in the SSP585 scenario (Figure S2). **By 2100, glacier volume could decrease by up to 79.6% under SSP585, compared to 38.6% under SSP126**. This will significantly alter the hydrological regime, with glacier melt and snowmelt contributing less, while rainfall-runoff will increase due to more liquid precipitation. The shift in peak runoff timing, from July to June by mid-century, will occur under higher warming scenarios (SSP370 and SSP585). By the end of century, the runoff magnitude will decrease, with a more significant reduction in snowmelt runoff and an increased contribution from rainfall-runoff (Figure S3). The **total runoff magnitude decreases significantly** and the shift in the peak total runoff becomes more evident by the end-of-century for SSP370 and SSP585 scenarios. The long-term average peak total runoff for the SSP370 scenario reduces by ~15.6% and shifts from July to June by the end of century. Whereas the reduction is larger in magnitude, i.e., ~23.3%, and shifts from **July to May for SSP585 scenario** by the end of century. These trends suggest that, despite increased rainfall, total runoff in the ZRB will decline due to the decreasing contributions from snow and glacier melt.

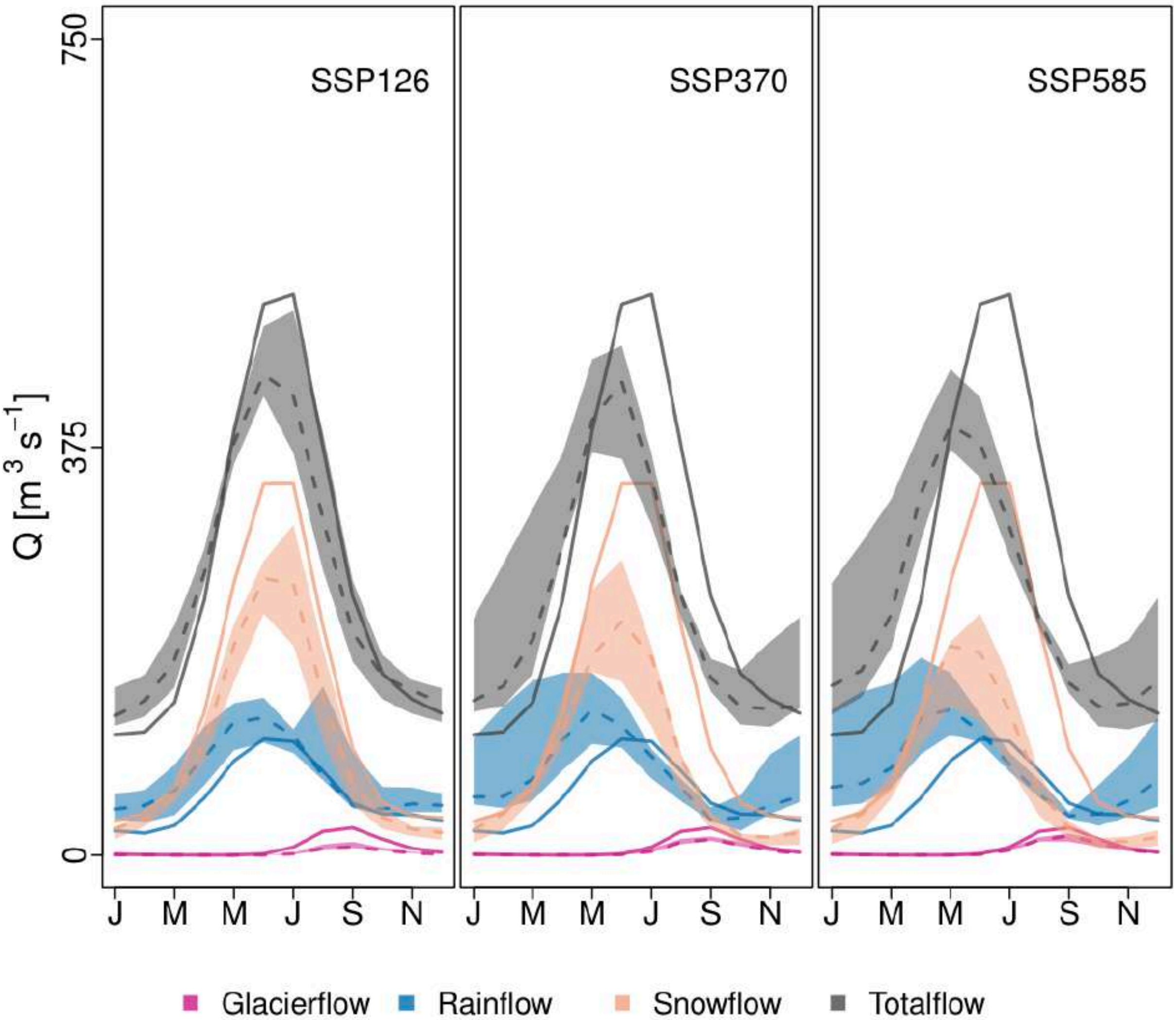


Figure S3: Seasonal changes in the hydrological regime for the mid-century (2036–2065) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The panels represent three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585. The shaded color represents the variability (minimum and maximum) of the flow contributors. The dashed and solid colored line represents the median of the five climate models and baseline flow (1991-2020).

The annual snow melt runoff will decrease by ~49% by the end of century for SSP585 scenario compared to initial conditions (2021). The decrease in snowmelt runoff is slightly compensated by the increase in rainfall runoff (~12%) by the end of century. **So, in future, the total annual runoff declines for all the SSPs.** The decline in total annual runoff is more pronounced in the SSP585 scenario (~16%) than in the SSP126 scenario (~11%).

Snowmelt delivers a steady water supply during spring and early summer, ensuring reliable irrigation for crops. The hydrological changes, i.e., **reduction in magnitude of total flow and shift in the peak total flow, will significantly impact the downstream water users.** For the agriculture sector, **a shift from a snowmelt-dominated to a rainfall-runoff hydrological regime means that the timing and availability of water for crops will change.** In particular, the small and medium-hold farmers in the mountains with significant snow dependence (in Matcha and Fondarya sub-basin) will be vulnerable to these seasonal changes. **This shift may require farmers to invest in improved water storage, adjust planting schedules, and adopt drought-tolerant crops.** Ultimately, adaptive management is essential to mitigate these impacts and maintain agricultural productivity in a changing climate. The farmers may need to shift the crop type and cropping pattern to cater for the consequences of snowmelt driven regime to a rainfall runoff regime.

Water allocation modelling of Zarafshon River Basin

Water supply and allocation is critical for the survival and well-being of people living in the basin. To address this challenge, an extensive scenario analysis was conducted using the WEAP water allocation model. The analysis of current water demand and unmet demand revealed that, despite the abundance of water resources in the basin (Figure S4), unmet demand is entirely attributable to limitations in the water supply infrastructure, including canals, pumps, and pipelines.

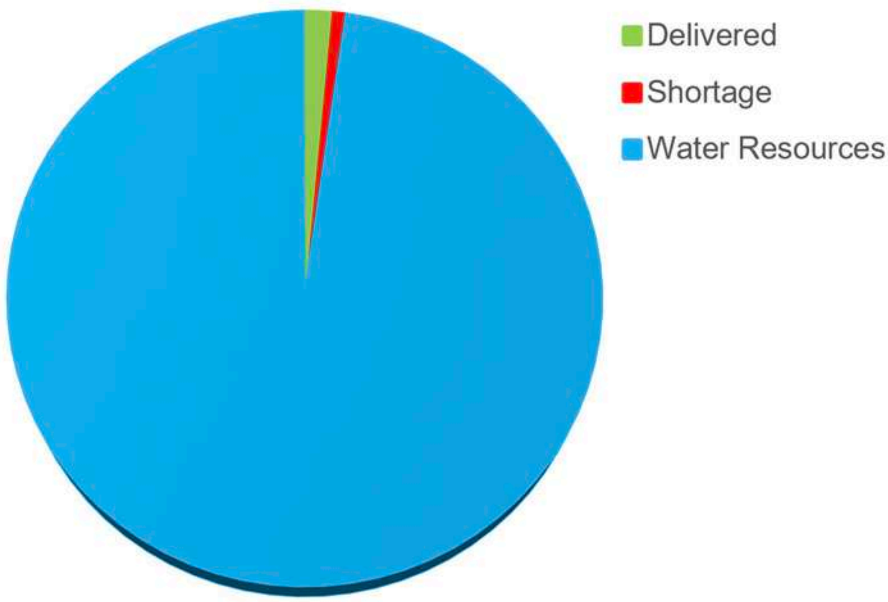


Figure S4: The graph illustrates that the combined water demand (delivered plus shortages) is considerably lower than the available water resources. Yet there is a significant shortage in water access, the supply infrastructure cannot meet the demand.

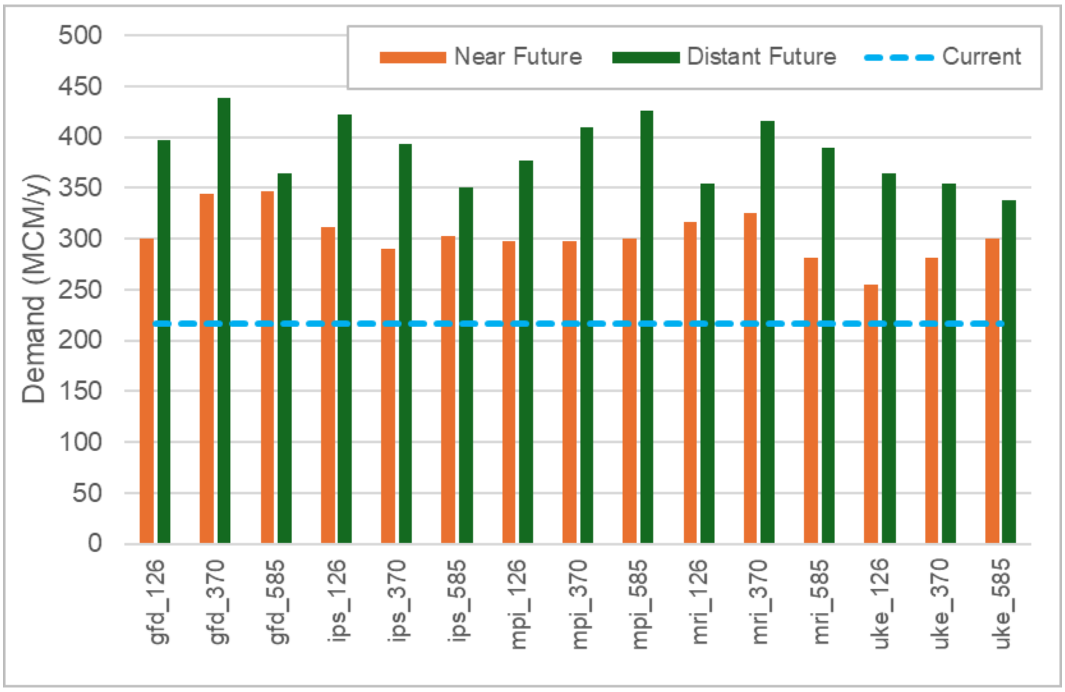
The scenarios were categorized into two groups: **projections** are factors that cannot be influenced by water managers (i.e., climate change and socio-economic development) and interventions, which represent actionable measures that can be implemented by water managers and policymakers.

Regarding the projections, both climate change and socio-economic development were considered. First, a series of exploratory **sensitivity analyses** were conducted to assess the impact of key assumptions on projected water allocation. **The results show that, given the substantial availability of water resources, neither climate change nor socio-economic development is expected to exacerbate water shortages.**

The **main conclusions of this explorative sensitivity analysis are:** (i) water demand is about 2% of water resources; (ii) water shortage, or better unmet demand, is mainly due to lack of water accessibility (water infrastructure); (iii) of the water delivered about 79% is consumed, the remaining flows back to the streams; and (iv) during a dry year water resources can reduce by around 25%.

Second, **a comprehensive climate change analysis** was conducted using the WEAP model to assess the full range of projected climate scenarios as described above. The total of 15 distinct GCM-SSP model combinations were evaluated, using the results of the SPHY model. The full set of SPHY outputs were evaluated using WEAP on its impact on key water allocation metrics, including total demand, supply, and unmet demand.

The most significant findings are: (i) water demands are expecting to increase by 18% to 60% in the near future, and 56% to 102% in the distant future; (ii) water shortages (unmet demand) will increase even further with average values of 113% for the near future, and 222% in the distant future; (iii) detailed analysis shows that this water shortage is mainly due to lack of water accessibility (water infrastructure) and not by a shortage of water resources (Figure S5).



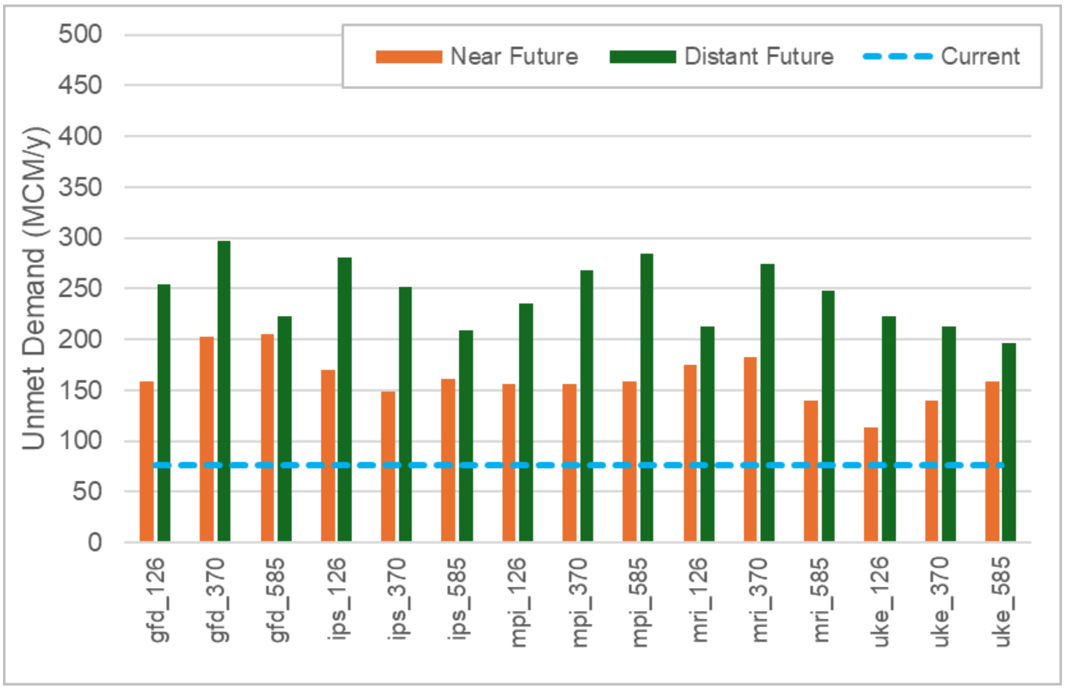


Figure S5. Average annual water demand (top) and unmet demand (bottom) for the 15 GCM-SSP combinations. Near Future is 2031-2050; Distant Future is 2061-2080; Current reflects 2001-2020.

The intervention scenarios focused on two key strategies: expanding supply capacity and improving infrastructure maintenance. The results demonstrate that both strategies, particularly in combination, significantly reduce unmet demand by addressing critical bottlenecks in water delivery systems. These findings highlight the **importance of targeted investments in supply infrastructure and maintenance to optimize water resource allocation and meet the growing demands of the basin's population.**

The main findings indicate that the interventions can effectively reduce water shortages. In the near future, average water shortages (across all GCM-SSP scenarios) can be reduced from 162 to 60 MCM/year, a 64% decrease. For the distant future, shortages can be reduced from 224 to 134 MCM/year, representing a 46% decrease (Figure S6).

Additionally, results show that **the impact of these interventions on overall water resources is minimal.** The total streamflow at the outlet of the Zarafshon River is projected to decline by only around 1%. The key message **is that water resources are not a critical limiting factor under any of the climate scenarios. However, supply capacity and infrastructure maintenance remain constraints on water availability.**

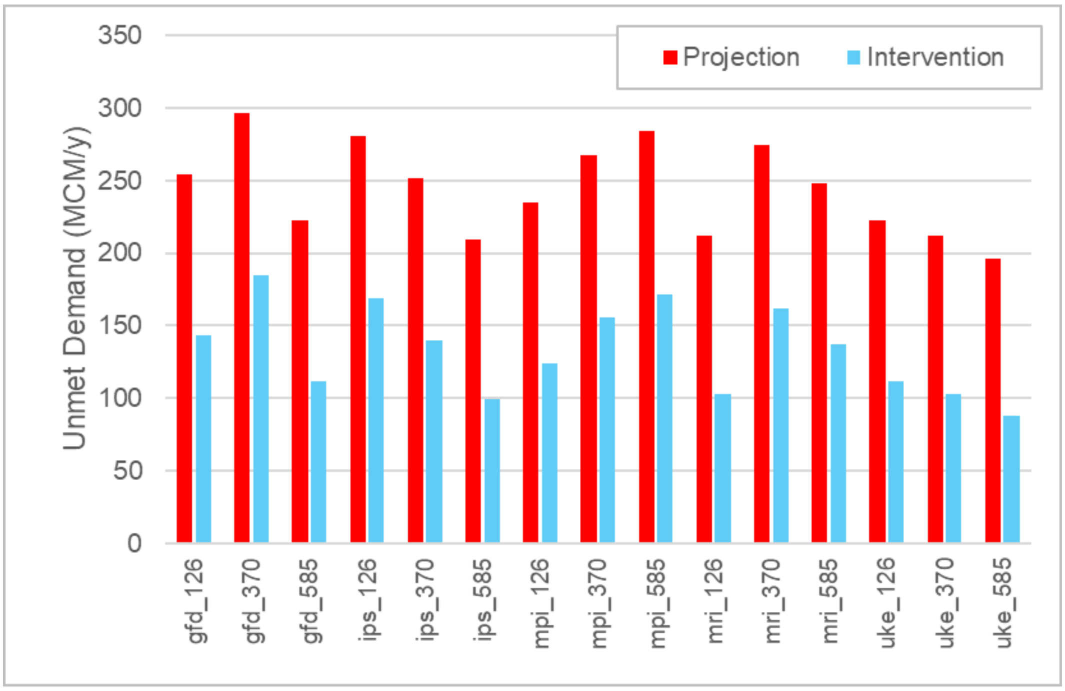


Figure S5. Average annual water demand (top) and unmet demand (bottom) for the 15 GCM-SSP combinations. Near Future is 2031-2050; Distant Future is 2061-2080; Current reflects 2001-2020.

Key recommendations

Addressing Data Gaps: Hydromet data is essential for glacio-hydrological research in mountainous regions like Tajikistan. This study relies on ERA5 reanalysis data downscaled using TopoSCALE, which has inherent biases, especially in data scarce regions like ZRB. The bias correction of downscaled forcing data with the limited ground-based observations may impose further uncertainties and challenges. Moreover, no or limited snow, glacier and hydrological (hydroposts) observations make it impossible to calibrate and validate the glacio-hydrological model.

These challenges in the project were addressed by **installing new meteorological stations and using the drone data to monitor the snow and glacier dynamics.** Drone technology is well-suited for analysing seasonal snow variability in harsh climates and complex topography due to its ability to capture high-resolution data, navigate rugged and remote areas, and conduct frequent, cost-effective surveys. They provide detailed insights into snow distribution, depth patterns, and properties with the use of multispectral cameras, which are difficult to obtain through traditional ground-based methods. Their flexibility, precision, and efficiency make them an invaluable tool for studying dynamic snow cover changes in challenging terrains.

The new monitoring stations and drone surveys will enable the Zarafshon RBO to further enhance the calibrated and validated glacio-hydrological and water allocation model co-developed by the FutureWater led consortium and several national stakeholders such as CGR, THA, IWP and TAU. **These models have been installed and deployed on the servers, workstations, and personal computers of the relevant staff of the aforementioned national institutions.**

Maintaining the current monitoring network is vital to secure continuous and reliable data. Additionally, establishing a comprehensive new network to monitor glaciers, snow, and permafrost will provide long-term records of key biophysical variables. Improved hydro-meteorological, snow, and glacier data will ultimately enhance model calibration and validation, of hydrological and water allocation models, required for the to develop effective strategies for sustainable water management and climate adaptation. Local stakeholders (CGR and THA) having mandate to collect the glacio-hydrological data are recommended to establish new high-altitude stations in the ZRB.

Upscaling the Approach: The SPHY and WEAP models have proven to be highly versatile and effective in ZRB, delivering **reliable and near-accurate simulations of cryospheric and hydrological processes.** As free, open-source tools, they enable seamless integration of ground-based and satellite-based data, offering a scalable and adaptable solution for extending their use to other river basins in Tajikistan and Central Asia. **Upscaling of the SPHY-WEAP models to other river basins in Tajikistan requires proper calibration and validation of the models by using the in-situ and secondary data.**

Alongside data monitoring, it is important to **implement soft interventions, such as capacity-building, knowledge sharing, and community engagement, to ensure a comprehensive approach to climate resilience.** Based on the project's experience, the following recommendations are proposed to the national stakeholders, bilateral donor agencies, financial institutions and MDBs to build resilience against the changing climate in ZRB and Tajikistan.

- **Data Management:** National stakeholders (for i.e., MEWR, THA, CGR, IWP) currently collect in-situ data independently and store it in analogue format, limiting interdisciplinary research, policy development, and collaboration. Implementing a robust centralised data management systems in the servers of the National Water Information System (NWIS) with open data sharing and standardized tools will enhance access to climate and water information, supporting deeper analyses and evidence-based decision-making.

- **Monitoring and Technology Investments:** Strategic investments in state-of-the art technologies (i.e. drone technology) and methods (models) are crucial for enhancing the frequency, accuracy, and coverage of cryosphere and hydro-meteorological monitoring in the ZRB and Tajikistan. Improved long-term data, especially at higher altitudes, will provide reliable insights into high mountains hydrological processes, supporting sustainable economic development in sectors like agriculture, energy, and infrastructure.

- **Mastering Proven Models:** National stakeholders (THA, CGR, IWP, TAU) should use proven, open source and scalable models (for instance, SPHY and WEAP) to ensure investments are impactful and avoid spreading the financial efforts with untested and expensive options. Focusing on a single, effective approach enables local stakeholders to build deep expertise and drive continuous improvements in monitoring.

- **Integrated Water Resources Management (IWRM):** IWRM is an iterative process that requires regular updates of the models to reflect evolving socio-economic priorities, policies, and plans. It is important to continuously update IWRM strategies in response to socio-economic changes, ensuring inclusion of youth and gender perspectives. Based on the learning from this project, MEWR should prioritize investments in enhancing supply capacity and maintaining water infrastructure to fully capitalize on available resources. It is recommended to implement and scale up these effective interventions while integrating continuous monitoring and modernization efforts into water management strategies. This approach will ensure that water shortages are minimized, and that the region's water supply infrastructure remains robust and resilient under future climate conditions.

- **Capacity building:** This project enhanced national technical capacity of national stakeholders (THA, CGR, IWP, TAU) by co-developing glacio-hydrological and water allocation models and techniques to assess and monitor cryospheric and hydrological changes, supported by over 150 hours of intensive technical training. By adopting a «training-of-the-trainer» approach and identifying young champions, the project not only improved sustainable water management skills but also ensured long-term capacity building beyond its duration. It is recommended to continue such efforts beyond the project duration.
- **International Partnership and Cooperation:** National stakeholders are encouraged to collaborate with regional and international partners to facilitate technology transfer, knowledge exchange, and joint initiatives. Leveraging global expertise and open data, these partnerships will address local challenges and enhance Tajikistan's development efforts.

1. INTRODUCTION

1.1 Background

Given the abundant freshwater resources in Tajikistan, water plays a crucial role in the country's socioeconomic development. More than 90% of agriculture production comes from irrigated lands and this sector employs over half of the workforce[1]. However, rising population and economic growth, coupled with the growing impacts of climate change in the region, calls for urgent action to ensure water availability and accessibility.

The Government of the Republic of Tajikistan (GoT) is implementing a Water Sector Reform Program to achieve a significant change in water access and use across multiple stakeholders.

The Water Sector Reform Program is led by the Ministry of Energy and Water Resources (MEWR). The Water Sector Reform Programme (2016-2025) was adopted based on the decision of the GoT under No. 791 as of 30 December 2015 to achieve the objectives and principles of the Water Sector Reform. River basin management and Integrated Water Resources Management (IWRM) are the main principles of the reform programme. As part of the Water Sector Reform Program, the capacity to improve water resources planning and allocation across sectors and users in the river basin zones must be strengthened. **Data and information about water supply resulting from snow and glacier melt remain a significant information gap and a bottleneck in planning the use and management of water resources in a sustainable manner.**

The **Integrated Rural Development Project / TRIGGER** (IRDP/TRIGGER) forms Component 1 «To boost added value of agricultural production" of the EU funded «Rural Development Programme II (RDP II). GIZ implements the activities of IRDP as part of the bilateral development project «Towards Rural Inclusive Growth and Economic Resilience (TRIGGER)" in Tajikistan co-funded by the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ).

The IRDP/TRIGGER Project provides technical support to the MEWR in Zarafshon[2] river basin, which is cryosphere-fed, as well as at the national level. Such technical support is comprised of technical advisory services, capacity building, training measures and support to formulate the Zarafshon River Basin Management Plan (ZRBMP) and improve access and use of irrigation water by small-scale farmers.

In addition to MEWR, other local relevant stakeholders foreseen as project beneficiaries are MEWR's national level and deconcentrated Water Resources Department of Zarafshon RBO, the National Water Information System (NWIS), the Center for Glacier Research (CGR), the Agency of Hydrometeorology (THA) under the Committee of Environmental Protection (CEP), the Institute of Water Problems, Hydropower and Ecology (IWP) and Tajik Agrarian University (TAU).

1 World Bank, Feature Story, 2020: Available here.

2 The name of the river is spelled as Zarafshon, Zeravshan and as Zarafshan. In general "Zarafshon" is used in Tajikistan and will be used here as well.

The IRDP/TRIGGER Project aims to improve the capacities for water resources planning and allocation of the Ministry of Energy of Energy and Water Resources (MEWR). In the context of formulation of the ZRBMP, glacio-hydrological and water allocation modelling seemed a sensible approach to enhance a coherent formulation of the river basin management plan to address the huge knowledge gaps of the MEWR on the mountain hydrology of ZRB and the climate change impacts on the cryosphere (seasonal snow and glaciers) feeding the Zarafshon river with a continuous water flow across the year, as well as to have a deeper look into water access as one of the main water resources challenges in the river basin (not water scarcity).

The approach of the IRDP/TRIGGER project to ensure a climate-resilient approach to water resources management and planning has been to incorporate glacio-hydrological and water allocation modelling to support the formulation of the ZRBMP and better understand the impacts of climate change on the glaciers and seasonal snow that provides the Zarafshon river with a continuous and steady flow across all the year.

Climate change impacts the different elements of the cryosphere differently, be it glacier melt, snow melt, rainfall or groundwater. Being the ZRB mostly cryosphere-fed, it resulted necessary to understand the magnitude of the impacts of climate change in each of the flow contributors.

In addition, **real climate-resilience in water resources planning requires to consider the magnitude of the changes of the river flow across time and space.** The "time" variable, is particularly relevant for water resources managers, planning officers and decision-makers. As it will be further developed below, the results of this report provide valuable information for the short-, medium- and long-term planning. For example, while short-term planning could be useful to operate a specific piece of infrastructure in ZRB (i.e. the gates of a dam or an irrigation channel), medium-term planning can be relevant for specific water sector regulation (i.e. surface and ground water abstractions) and long-term planning to devise clear strategies to address climate adaptation, including depicting new infrastructure models or approaches to achieve greater climate change adaptation and mitigation.

Hydrological modelling is an important tool supporting the formulation of the ZRBMP, providing essential insights for water resource management, especially in understanding water security at basin level. It enables accurate assessments of water availability, flow patterns, and potential impacts of various management scenarios, crucial for informed decision-making. Given the arid climate and increasing water demands in the Zarafshon River Basin, this modelling is particularly important for developing effective strategies to address water-related challenges and ensure the long-term sustainability of water resources.

An additional annex has been added to the RBMP as a summary of the hydrological modelling report prepared by the Consortium. This hydrological modelling summary is also briefly mentioned in Section 5 of Book 2 "Assessment of the ecological condition and key problems of the river basin" of the RBMP, which includes citations and referencing to this hydrological modelling report.

The results of this hydrological and water allocation modelling report have been used to support the formulation of the RBMP to ensure that planned river basin interventions are commensurate and coherent with the availability of water resources and the locations and communities where water access remains a challenge. It is worth noting, that hydrological and water allocation modelling is not mandatory per the official guidelines of Tajikistan regarding the formulation of river basin management plans. Such guidelines mandate only a water balance.

Climate change in Tajikistan poses a serious threat to the country's sustainable development. A new World Bank report[3] highlights that climate shocks, such as increased variability in river flows and more frequent natural disasters, are already threatening energy and water security. GDP per capita is expected to fall by 5-6% by mid-century, which could lead to an increase in the number of poor people per 100,000. The World Bank report is an important tool for Tajikistan, providing evidence-based data and recommendations for developing adaptation strategies. It helps prioritize investments in climate-resilient infrastructure, sustainable agriculture, and landscape restoration. In addition, the report highlights the need to strengthen the capacity of local authorities and mobilize rural communities to respond effectively to climate challenges.

1.2 Key objectives

In this project, a glacio-hydrological model (**S**patial **P**rocesses in **HY**drology–**SPHY**) and a water allocation model (**W**ater **E**valuation **A**nd **P**lanning–WEAP) are set up to understand the hydrological regime (contributors to the streamflow) for baseline and future conditions, water supply and demand scenarios at different temporal and spatial scales. The ZRB SPHY model, which covers the entire upstream region of the transboundary Zarafshon River just before it enters Uzbekistan, focuses on the changes in total water availability of the entire upstream region. In contrast, the ZRB WEAP model focuses on water supply, demand and scenarios.

The key objectives of this report are as follows:

1. **Quantify** historical climate trends (precipitation and temperature), flow composition, and key water balance components of the ZRB using the SPHY glacio-hydrological model.

2. **Estimate future climate trends**, assess climate change impacts on the cryosphere (snow and glaciers) in the ZRB, and analyse effects on river flow at seasonal and decadal timescales up to the century's end (2100). The report also aims to quantify the changes in each flow component's contribution (snow melt, glacier melt, rainfall-runoff and baseflow) at multiple time horizons in the future.

3. **Assess upstream-downstream linkages**, evaluate water demand-supply imbalances, and analyse water allocation across sectors using scenario-based analyses in the WEAP model. This includes identifying water access shortage hotspots in the ZRB.

4. **Share and communicate** the results of the glacio-hydrological and water allocation modelling carried out in the ZRB in the framework of the technical assistance provided by the IRDP/TRIGGER project to the MEWR of Tajikistan.

3 Tajikistan Country Climate and Development Report, World Bank.

5. **Provide recommendations to address gaps in cryosphere monitoring** in Tajikistan and promote the scaling up of glacio-hydrological and water allocation technology investments for climate adaptation.

1.3 Description of the services and outputs

Since the cryosphere[4] governs the availability of freshwater in Tajikistan, and particularly in Zarafshon river basin, GIZ commissioned Consortia Partners Future Water, Utrecht University and University of Fribourg (the "Consortia Partners") to fill the aforementioned information gap by **improving the capacity to i) collect, assess, and use water supply data from snow and glacier melt, and ii) perform hydrological modelling to inform water resources allocation and multi-sectoral planning in ZRB considering the impacts of climate change.** The services provided by the Consortia Partners entail three core components: data collection, modelling, and capacity building.

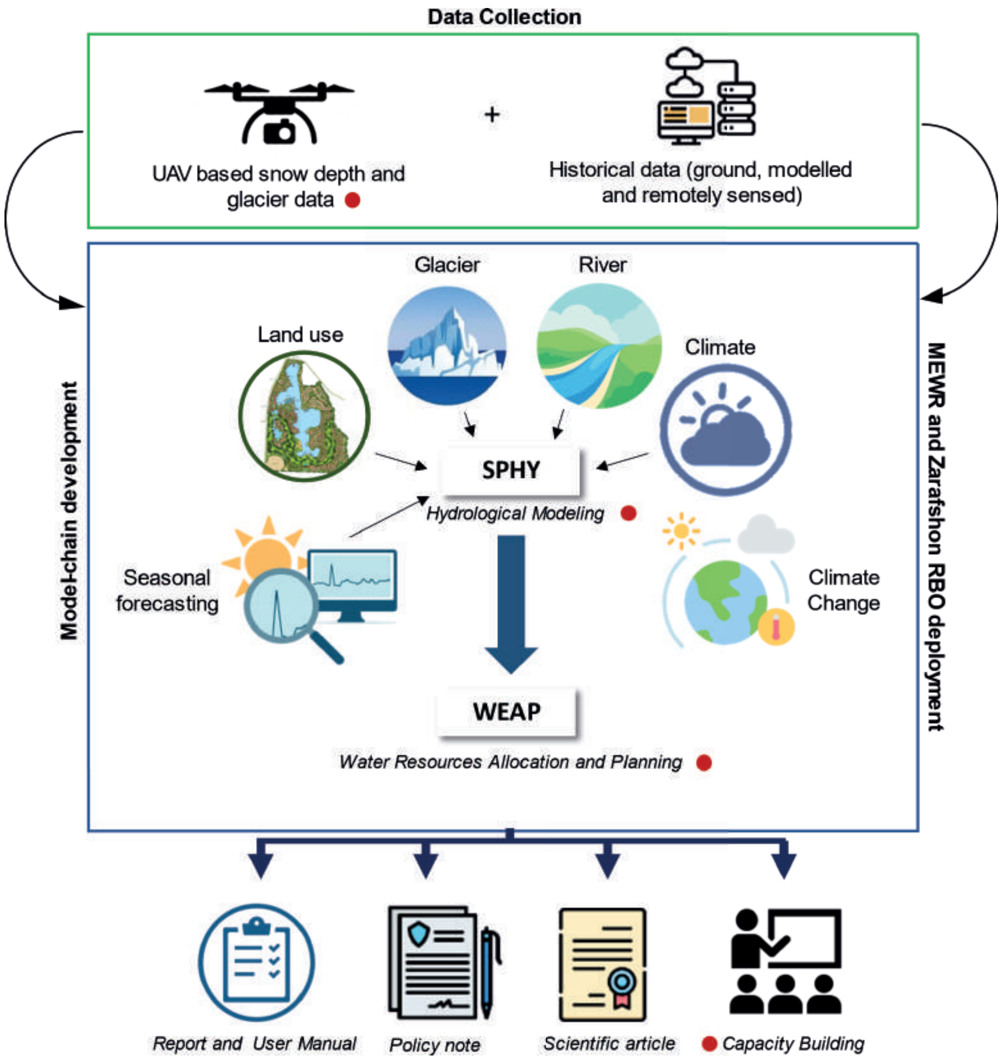


Figure 1: Project framework and key components (red dot denotes the capacity building training)

4 Cryosphere includes the components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground, and solid precipitation.

Data collection has included both field monitoring campaigns using UAVs and retrieving historical records which could either be past in-situ observations, or remotely sensed or modelled data. **Two glacier expeditions to train local stakeholders on the use of drone technology to collect cryosphere data at the GGP glacier in ZRB were supported in September 2023 and September 2024.**

The comprehensive datasets were used to set up, calibrate and validate SPHY v3 and WEAP models. The Consortia Partners used the model chain to provide the flow predictions in the short, medium, and long-term horizons. The SPHY-WEAP model chain was deployed in the MEWR's servers, including that one based in the Zarafshon RBO premises in Ayni.

The results of the model chain were used to develop a comprehensive policy guidance note, proposing strategies and a way forward to develop a robust approach to climate-resilient integrated water resources management (IWRM) in the ZRB to ensure both water availability and accessibility across the river basin.

The specific outputs or products of these services are as follows:

1. **A Fully calibrated and validated SPHY (glacio-hydrological) and WEAP (water allocation) models.**

2. **User manuals, training materials, and resources** to support the application of the model chain (SPHY-WEAP).

3. **A Technical Report (this report)** that integrates the climate change-related outputs generated and the SPHY and WEAP model analysis and results, climate change impacts assessment, upstream-downstream linkages, assessment of demand-supply imbalances, allocation of water to various sectors, and assessment of scenario-based analyses. Including detailed descriptions of the methodologies used, results obtained, and interpretations of the findings.

4. **A Policy Note** that captures all the knowledge generated during contract implementation and contains future guidance on modelling efforts, snow, and glacier monitoring, and their role in improving climate resilience, based on lessons learned and results obtained through the implementation.

5. **A Peer-reviewed Scientific Manuscript** that gives an understanding of the impact of climate change on water balance components, water availability, holistic water allocation for different sectors, and if-else scenario analysis.

Further, several trainings, workshops, meetings and glacier monitoring campaigns were organised during the project duration (March 2023 to September 2024) as shown in Table 1 below.

Table 1: Set of trainings conducted with mode/location, brief content, and dates. 'Offline' refers to the in-country training conducted by international experts whereas 'Hybrid format' training refers to the participants gathering at the same location in Dushanbe while the international experts provided the training online.

Training Title	Format	Training Content	Training Date
Training 1. Introduction to SPHY and WEAP	Offline, Dushanbe	Water balance assessment, water allocation scenarios, SPHY and WEAP introduction	September, 2023
Training 2. Seasonal snow and glacier monitoring techniques using UAV	Offline, GGP Glacier	First GGP glacier expedition, drone demo, data collection and analysis	September, 2023
Training 3. WEAP Zarafshon model setup based on observed data	Hybrid, Dushanbe	Advanced WEAP model setup based on observed data	November, 2023
Training 4. Glacio-hydrological modelling with SPHY for the ZRB in Tajikistan	Hybrid, Dushanbe	Advanced SPHY model setup based on observed data	December, 2024
Training 5. Water allocation modelling for the ZRB in Tajikistan	Hybrid, Dushanbe	Advanced training on WEAP scenarios development	April, 2024
Training 6. Advanced glacio-hydrological and water allocation modelling using SPHY and WEAP models for the ZRB in Tajikistan	Offline, Dushanbe	Model chain coupling and deployment of the NWIS and RBO.	June, 2024
Training 7. Water management using SPHY and WEAP models for Zarafshon River Basin	Offline, Wageningen, Netherlands	Drone demo, data collection and processing and final model chain validation	August, 2024
Training 8. Assessing impacts of climate change cryosphere and water resources in ZRB using SPHY and WEAP models	Offline, Dushanbe	Climate models selection, downscaling, impact assessment on cryosphere and changes in hydrological regime	September, 2024
Training 9. Integrating Drone Data Collection Technologies with SPHY and WEAP for Enhanced Cryosphere Monitoring and Water Management in the Zarafshon River Basin	Offline, GGP glacier	Second GGP glacier expedition, drone demo, data collection and analysis	September, 2024

2. RESULTS

2.1 Hydrology

This section presents the baseline hydrological regime, flow contribution, spatial differences in flow contributors, and water balance components of the water cycle in the ZRB (of Tajikistan part only). The analysis and results in this section are based on the modelled natural flow from the SPHY model. The SPHY results do not incorporate any water infrastructure and human water abstractions, these elements are incorporated in the WEAP model that deals with water demand and access. For more details regarding the SPHY model, readers are referred to 'Annex 2: Explanation of the model, data and methodologies' of this report. Overall, this section contributes to a better understanding of the historical hydrological regime of the region.

ZRB, with an area of 17,700 km2 in Tajikistan, covers diverse geological formations ranging from the alpine zone, 3200–3500 m above sea level. The ZRB encompasses a total glacier area of 437.9 km2, with the Zarafshon glacier being the largest among the 632 glaciers. This glacier stretches over 27.8 km in length and covers an area of 87.2 km2. For more information regarding the key features of the study area readers are referred to 'Annex 1: Key features of the study area' of this report.

Box 1: Water balance

Baseline: The 'baseline' or 'reference' or 'present-day' refers to the 30 years of historical conditions from 1991–2020.

Future: Future refers to the period between 2021–2100. To investigate the climate change impacts in the future, the future period is further divided into two slices of 30 years; mid-century or medium-term horizon (2036–2065) and end of century or long-term horizon (2071–2100).

Hydrological fluxes: The outcomes from the SPHY hydrological model. For instance, snow melt, glacier melt, rainfall-runoff and baseflow.

Flow contribution: The contribution of snow melt, glacier melt, rainfall-runoff, and baseflow to the total runoff (expressed in %).

Seasonality: Mean monthly changes over the course of the year for a specified time period. Generally, calculated for the 30 years' time period.

Average long-term: Mean annual changes over the course of a specified time period. Generally, calculated for the 30 years' time period

Water balance: The water balance from SPHY model refers to the natural flow so do not incorporate any water infrastructure and human water abstractions.

2.1.1 Baseline

The parameters from the calibrated ZRB-SPHY model are used to understand the changes in baseline (Box 1) hydrological fluxes between 1991–2020 period. For more details regarding the model inputs, setup, calibration and validation, readers are referred to 'Annex 2: Explanation of the model, data and methodologies' of this report.

At the outlet of the ZRB SPHY model domain, **just before the Zarafshon River enters Uzbekistan, the snowmelt-runoff is the dominant contributor (53%) to the total runoff** (Figure 2). The contribution of snowmelt runoff begins to rise in April and reaches its peak during June-July. **Although the majority of precipitation falls as snow in the spring season (March-May), the melting peaks in June-July when temperatures are warmer.** The snow contribution again ceases in the winter season when the temperature is low and solid form of precipitation is stored as snow at higher elevation in ZRB.

The baseflow is the second-largest contributor, 23.1%) to the total runoff. **The large amount of baseflow is attributed to the fact that a large portion of snowmelt runoff is infiltrated into the rootzone, subzone and eventually to the groundwater layer in the model.** The baseflow drains water to the river channel all-round the year but its contribution increases in the dry and cold season (September, October, November, December, January, February). **The contribution of rainfall-runoff, the third largest contributor (21.3%) to total runoff, peaks in June and ceases rapidly after August.** The glacier melt contributes about 2.6% to total runoff. The glacier melts when the temperature is above zero on the glacier surface. The glacier melt starts in May and peaks in August/September when the temperatures are high. **Even though the annual contribution of glaciers is the smallest at the outlet, its monthly contribution reaches ~11% in September when there is less water in the river system.**

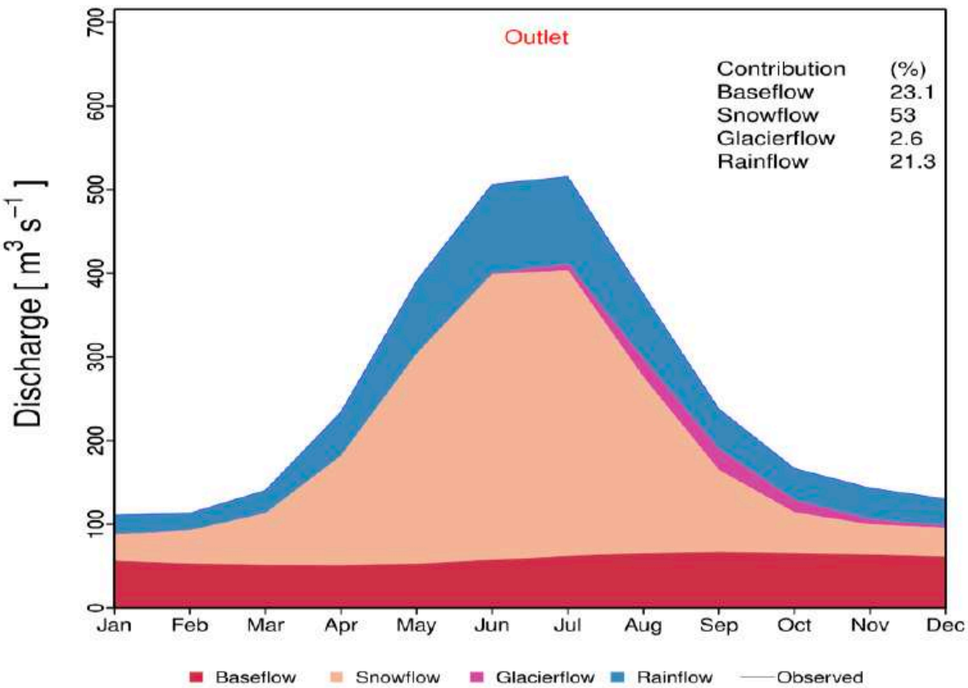


Figure 2: Baseline averaged monthly runoff with the distinction of flow components (base, snow, glacier, and rain-runoff flow at the outlet of the ZRB(just before the Zarafshon River enters Uzbekistan) for 1991–2020. The top right part of the figure shows the contribution of stream flow contributors to the total flow (expressed in %).

The spatial runoff patterns reveal that the snow and glacier melt runoff contribution is high for the upstream river reaches of the ZRB (Figure 3). The Zarafshon glacier contributes around 70% to the total runoff in the upstream reaches of 'Matcha' river. Whereas the snow melt contribution is larger for the upstream Fondarya River tributaries. In upstream tributaries of the Fondarya River, the snowmelt contribution is around 90%. **Overall, the upstream ZRB catchment is mainly dominated by the snowmelt runoff and glacier components. For the lower part of the basin, the flow is dominated by the snow and the baseflow components.**

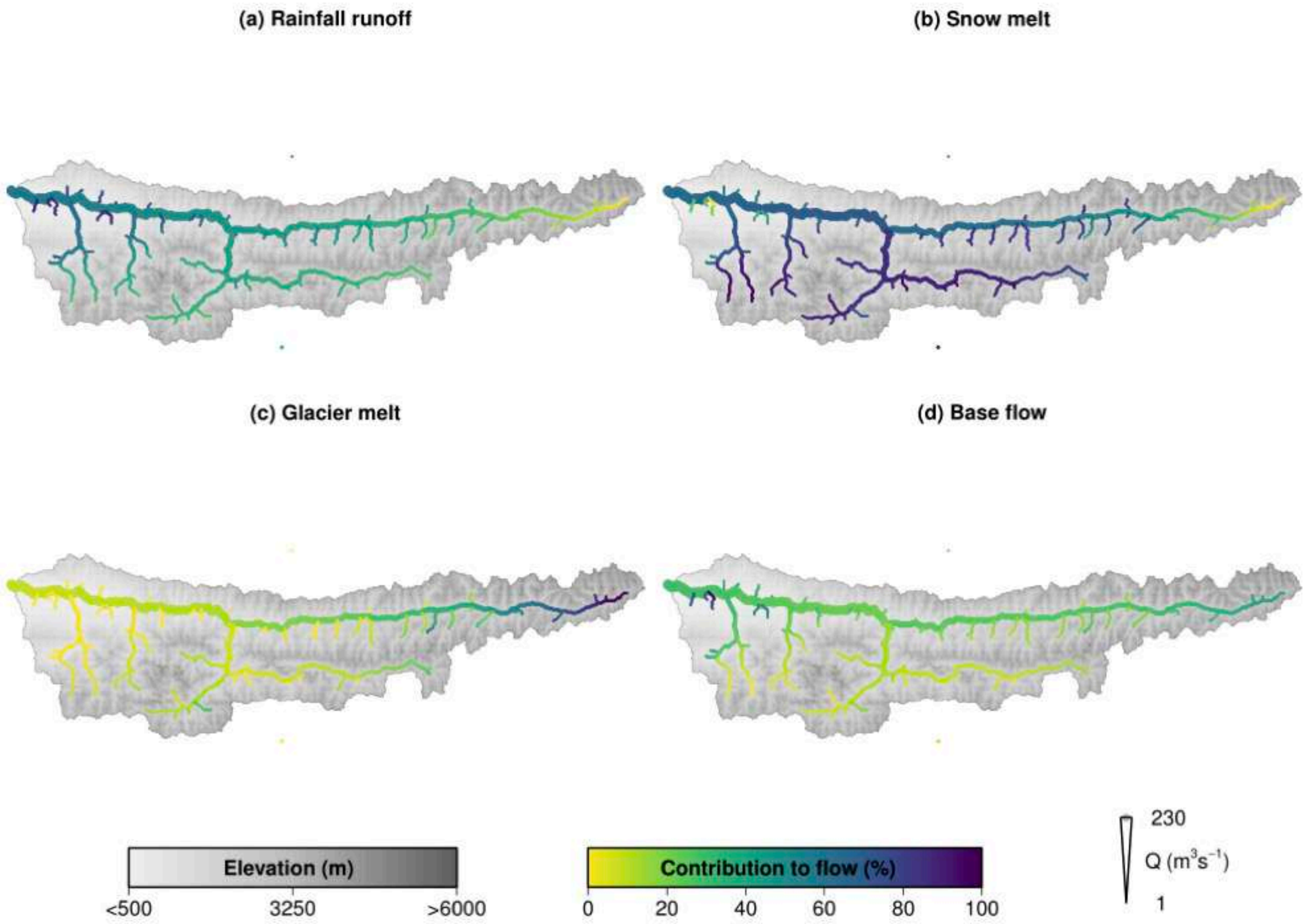


Figure 3: Spatial contribution patterns of the flow components for the ZRB (just before the Zarafshon River enters Uzbekistan) for 1991–2020. (a) Rainfall-runoff (b) Snow melt runoff (c) Glacier melt runoff and (d) Baseflow The background is elevation; color represents the contribution, and size represents the discharge values.

There is a large annual variability in the flow hydrograph patterns for the ZRB (Figure 4). The variability is associated with the physiographic and climatic characteristics, such as variability in precipitation, temperature, changes in snow and glacier ice reserves over the seasons and years. The maximum peak total flow in the baseline period is found to be 772 m^3/s in July 2003. The modelled peak discharge timing aligns with reported flooding in Sughd and Panjakent region[5,6]. This is one of the worst natural disasters when widespread heavy winds and rain resulted in floods across Tajikistan, affecting 10000 people and damage worth millions of dollars.

5 https://reliefweb.int/disaster/fl-2003-000273-tjk

6 https://go-api.ifrc.org/publicfile/download?path=/docs/appeals/rpts03/&name=tajikflood03a1.pdf

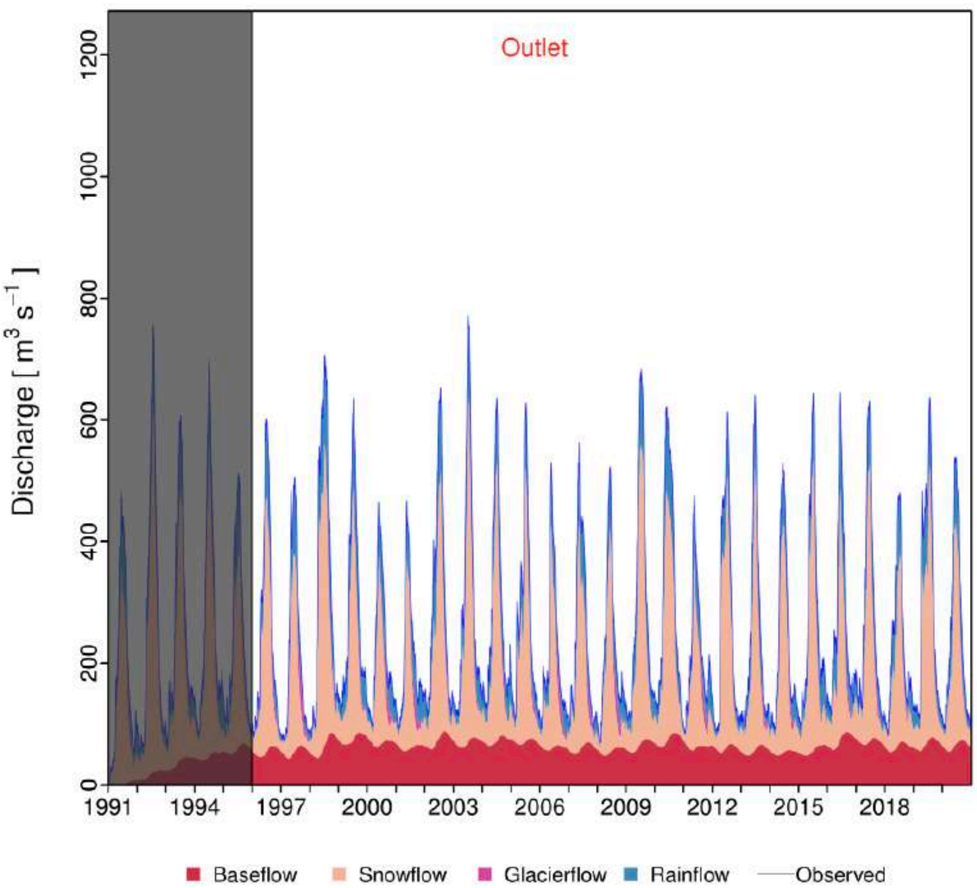


Figure 4: Baseline daily runoff with the distinction of flow components (base, snow, glacier, and rain-runoff) at the outlet of the ZRB basin (just before the Zarafshon River enters Uzbekistan) for 1991–2020. The grey rectangle represents the model spin up period (1991-1995).

The linear trends at the annual timescale suggest that the total runoff has slightly decreased in the past 30 years (Figure 5). **This is attributed to the consistent decline in all runoff components.** Snow and glacier flows have experienced a slight decrease in recent years, primarily due to the ever-increasing temperatures in recent decades. Higher temperatures reduce the solid fraction of precipitation, leading to a decrease in snow runoff over time. Glaciers form as snow compacts into ice and flows outward under its weight. They grow or remain stable when snow accumulation matches or exceeds melting.

However, reduced snowfall causes glaciers to retreat, exposing more ice to solar radiation and speeding up melt. Rising temperatures and deposition of black carbon from industrial and agricultural activities further accelerate glacier retreat and reduce runoff. The accelerated melting of glaciers from rising temperatures has reduced glacier area and decreased runoff.

The amount, timing, and spatial patterns of runoff contributors play a key role in providing water for upstream and downstream demands in ZRB. The seasonal variations in the precipitation and temperature patterns are reflected in the runoff trends. However, on a seasonal scale, there are contrasting trends compared to the annual scale (Figure 6). **The seasonal analysis shows that total runoff trends decrease during the summer and autumn seasons but increase in the spring and winter.** The increase in total runoff during spring is attributed to the early melting of snow in recent years in the ZRB.

Seasonal patterns in precipitation, temperature, snow accumulation, and glacier melt drive diverging seasonal runoff trends.

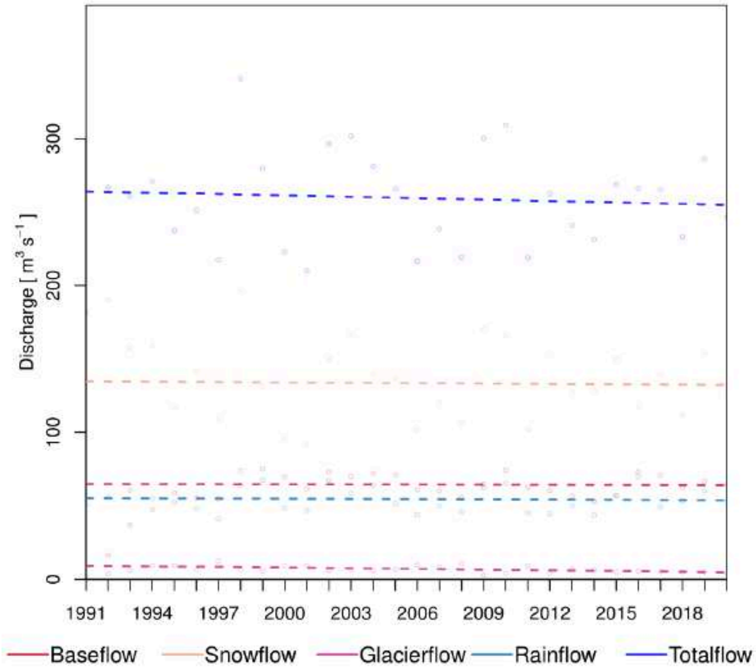


Figure 5. Linear trends of average annual runoff components (base, snow, glacier, and rain-runoff flow) at the outlet of the ZRB basin (just before the Zarafshon River enters Uzbekistan) for 1991–2020. Note: the trends are calculated excluding the model warmup period (1991-1995).

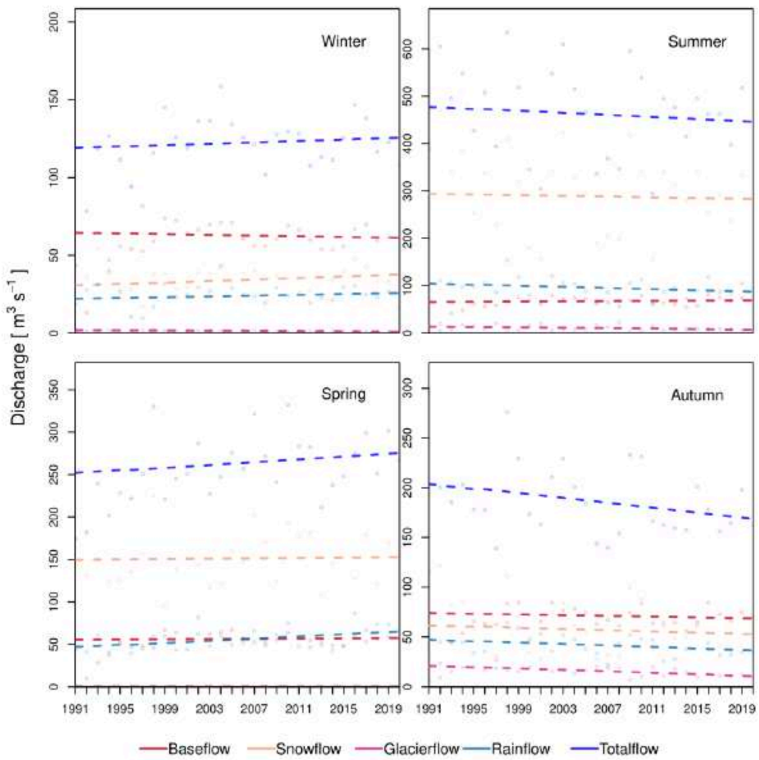


Figure 6. Linear trends of average seasonal runoff components (base, snow, glacier, and rain-runoff flow) for Winter (DJF), Spring (MAM), Summer (JJA), and Autumn (SON) at the outlet of the ZRB basin (just before the Zarafshon River enters Uzbekistan) for 1991–2020. Note: the trends are calculated excluding the model warmup period (1991-1995).

2.1.2 Climate change impacts on the cryosphere

In recent decades, the cryosphere of the high mountains of Asia (HMA) region including Tajikistan has experienced significant changes (Kang et al., 2010; Khanal et al., 2023). These changes have impacted glaciers, snow, ice, and local water systems. Notable effects include rapid glacier shrinkage, reduced snow cover, melting permafrost, changes in areas with frozen ground, and more frequent snow and ice avalanches (Bolch et al., 2012; Immerzeel et al., 2020). In the future, climate change is expected to cause more changes in ice and snow reserves (Box 2), which will in turn affect the hydrological cycle (Khanal et al., 2021; Kraaijenbrink et al., 2017b).

Box 2: Response of climate change on hydrological processes and hydrological regime

Response

The response of different hydrological processes to climate change varies significantly depending on both spatial and temporal scales, ranging from catchment to river basin levels and from sub-daily to decadal periods. Rainfall-runoff processes tend to react quickly to climate changes, while glacier melt responds on much longer timescales, from decades to centuries (Khanal et al., 2021; Wijngaard et al., 2017a). Glacier melt is heavily influenced by the current ice volume and the period considered. If there is enough ice, continued warming will lead to increased glacier melt. However, as glaciers shrink, the overall melt generation will gradually decrease over time. The time it takes for glacier melt to reach its peak is related to the volume of ice present. For snow, warming affects multiple processes: higher temperatures speed up snowmelt but also reduce the amount of precipitation that falls as snow, which eventually decreases the contribution of snowmelt to total runoff. The response of snow processes to climate change can range from seasonal to annual timescales.

Hydrological regimes

The classification of hydrological regimes is typically done based on the contributions of different water sources, such as snowmelt, glacier melt, and rainfall (Khanal et al., 2021). The Glacial hydrological regime is primarily influenced by glacier melt, whereas the Nival regime is driven by snowmelt. The Glacial-Nival regime combines influences from both glacier melt and snowmelt, resulting in peak flows from late spring to summer, with glacier melt sustaining flows into late summer and dry periods. The Nival-Pluvial regime is influenced by both snowmelt and rainfall. Climate change is altering these regimes, particularly in glacier- and snowmelt-dominated basins, where rising temperatures reduce glacier and snow contributions while increasing the influence of rainfall. Understanding these shifts is crucial for water resource management, especially in river systems like the Amu Darya and Syr Darya, which are highly vulnerable to climate change impacts.

Box 3: Climate change scenarios

Intergovernmental Panel on Climate Change (IPCC): The IPCC is the international body tasked with assessing the science of climate change. Since 1988, the IPCC has informed policy makers on (a) the physical science of climate change (b) its impacts and (c) future risks options for adaptation and mitigation. The IPCC released its latest Sixth Assessment Report (AR6) in 2021.

Coupled Model Intercomparison Projects phase 6 (CMIP6): The CMIP is a collaborative framework established in 1995 by the World Climate Research Programme's Working Group on Coupled Modelling. Its primary goal is to improve our understanding of climate change by coordinating climate model experiments across various international research institutions. The latest phase, CMIP6, includes around 100 distinct climate models from 49 different modelling groups.

Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): The ISIMIP offers a framework for gathering consistent climate impact data across various sectors and scales. It provides a unique opportunity to examine interactions between climate change impacts through standardized scenarios. ISIMIP3b group I simulations utilize historical climate change data from CMIP6 ensembles, combined with observed historical socio-economic factors.

Shared Socioeconomic Pathways (SSPs): SSPs are scenarios that describe potential future global developments considering factors such as population growth, economic development, and technological progress. They serve as narratives to explore how different socioeconomic trajectories might influence greenhouse gas emissions and, consequently, climate change.

Representative Concentration Pathways (RCPs): The RCPs describe different climate change scenarios, all of which were considered possible depending on the amount of greenhouse gases (GHG) emitted in the years to come. The SSP-RCP scenarios combine baseline socio-economic narratives (the SSPs) with different emissions trajectories (based on the RCPs). The SSP-RCP scenarios impose global warming targets on the baseline SSP scenarios using the radiative forcing levels of the RCP scenarios.

SSP1-Sustainability (Taking the Green Road): SSP1 focuses on a sustainable, green future with low inequalities, fostering global cooperation and ambitious climate action.

SSP3-Regional rivalry (A Rocky Road): SSP3 imagines a fragmented world, marked by regional conflicts, economic challenges, and limited global cooperation, making climate mitigation more difficult.

SSP5-Fossil-fueled Development (Taking the Highway): SSP5 envisions rapid, fossil-fuel-driven growth, prioritizing economic expansion over climate policies, leading to high emissions and environmental strain.

In ZRB the volume and area of the glaciers in the future are declining rapidly for all the SSP (Box 3) scenarios (Figure 7). Before 2040 the decline in area and volume in the SSP scenarios are more or less similar. However, after 2040 the differences in the different SSP scenarios become more prominent. This aligns with the 'hockey stick' patterns seen in the temperature time series in different SSP scenarios after 2040 (see Figure 57 in Annex 2: Explanation of the model, data and methodologies). The larger decrease in volume and glacier area in SSP585 compared to SSP126 is attributed to the warmer temperatures in SSP585. The magnitude of the decline of glacier volume and area is different for each scenario (Table 2). **As per SSP245 and SSP585, by 2070 the ZRB will lose about half of the glacier volume compared to the initial state of 2020.** By the end of century (2100), the glacier volume lost by SSP585 scenario (79.6%) is more than double compared to the SSP126 scenario (38.6%). A similar pattern is seen for the reduction in glacier area for the different SSP scenarios. **For all SSP scenarios, the reduction in glacier area is larger compared to the reduction in volume of the glaciers (38.6% in SSP1 for glacier volume compared to 44.0% in SSP1 for glacier area). This is due to the fact that the small glacier with less ice volume will disappear rapidly in the future.**

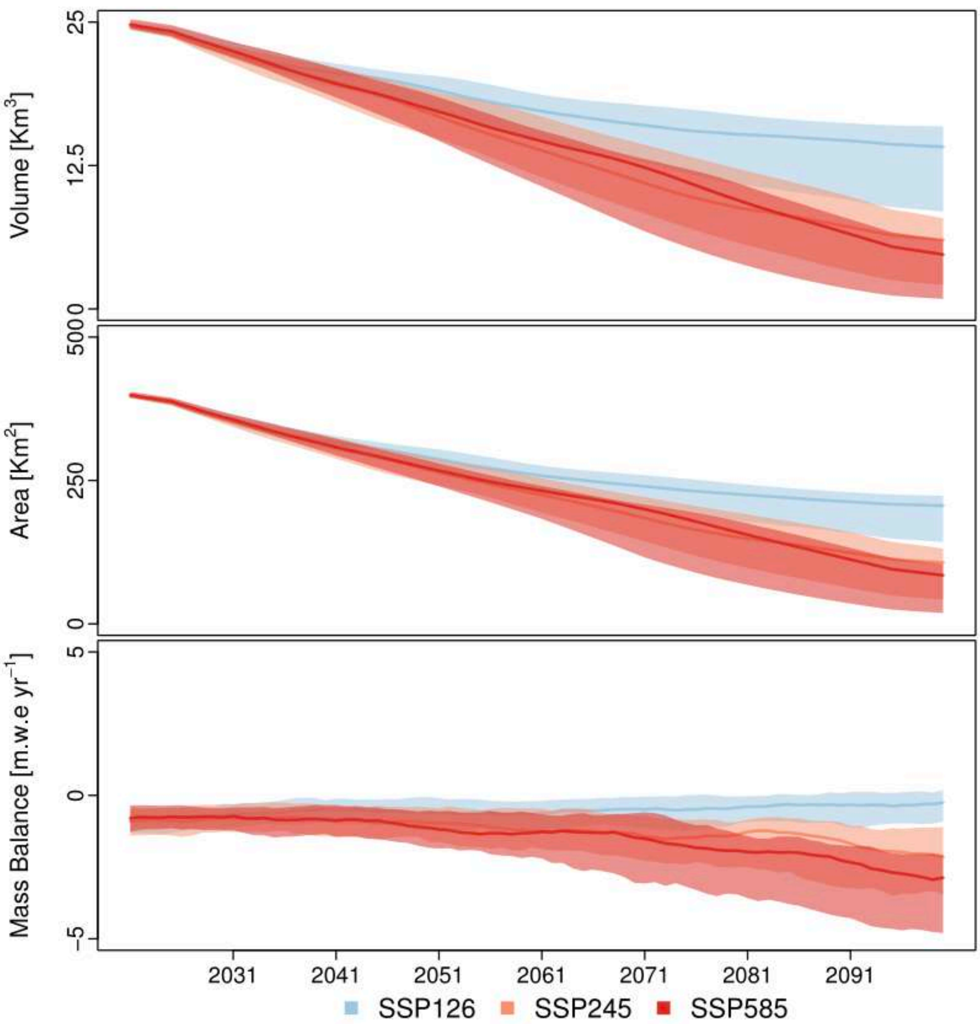


Figure 7. Long-term changes in the total volume (top), area (middle), and mass balance of all the glaciers in the ZRB (just before the Zarafshon River enters Uzbekistan). The shaded color represents the three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585. The bandwidth represents the variability (minimum and maximum) of the five climate models with each SSP. The solid-colored line represents the median of the five climate models.

Table 2. Percent reduction in volume and area expressed as % in the three SSP scenarios compared to the initial state (2020) of the glacier in the ZRB. The number represents the median of the five climate models in each SSP scenario.

	Volume [%]			Area [%]		
Year	SSP126	SSP245	SSP585	SSP126	SSP245	SSP585
2030	8.7	9.2	8.3	10.2	10.1	9.6
2040	15.4	18.2	19.2	19.3	20.5	21.1
2050	20.9	29.6	28.7	26.0	31.3	31.1
2060	27.9	41.5	39.0	33.0	41.0	39.8
2070	32.7	52.8	48.0	37.4	50.9	47.5
2080	35.5	62.5	60.3	40.5	60.0	58.2
2090	36.9	68.6	71.3	42.8	66.0	69.1
2100	38.6	73.7	79.6	44.0	70.9	77.2

2.1.3 Future impacts on the hydrological regime

Changes in the seasonality

To understand the hydrological changes in the future, different time scales i.e., seasonal and decadal and time slices i.e., mid-century (2036–2065) and end-of-century (2071-2100) are investigated (Box 2).

From 2036 to 2065 (mid-century)

On a seasonal scale for the mid-century, the glacier melt runoff decreases in all the SSP scenarios compared to the baseline scenario (Figure 8). The snowmelt runoff significantly decreases in all the SSP scenarios (Table 3). The decline is larger for the SSP585 compared to the SSP126 scenario (Box 4). **The rising temperature results in a decreasing fraction of solid precipitation (i.e., snowfall), which consequently results in decreased snowmelt runoff by the mid-century.** Significant reduction in snow-melt runoff is observed in winter months (September to December). The maximum decrease in snowmelt runoff for SSP370 and SSP585 occurs in October, with values dropping to -41.8% and -44.6%, respectively. However, in terms of absolute changes, the largest changes are observed in the summer months (from May to August) (Figure 8 and Figure 10). **The rainfall-runoff contribution is expected to increase significantly by mid-century across all SSP scenarios, primarily due to the rise in liquid precipitation (i.e., rainfall) driven by intensified warming. Interestingly, the timing of peak total runoff changes from July to June** by the mid-century for SSP370 and SSP585 scenarios. **The increasing contribution of rainfall-runoff and the decreasing contribution of glacier and snow runoff are the prime reasons for the detected shift in peak total runoff from July to June for mid-century.** The total flow decreases during the summer months, with the largest reduction, ~22 % for SSP370 occurring in August for all scenarios (Table 3).

Table 3. Climatological changes (expressed as % compared to the baseline flow) in the snow and total runoff for the mid-century (2036–2065) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan).

	Snow melt runoff			Total runoff		
	SSP126	**SSP370**	**SSP585**	**SSP126**	**SSP370**	**SSP585**
Jan	-18.1	-31.0	-23.5	23.5	17.2	35.7
Feb	-13.2	-11.7	-8.4	29.7	20.6	34.5
Mar	-7.4	-17.8	-10.8	28.7	20.9	47.2
Apr	-12.2	-19.7	-13.1	16.4	7.3	22.2
May	-18.2	-24.9	-23.4	2.4	-5.4	0.8
Jun	-25.5	-28.3	-29.9	-9.4	-12.4	-13.7
Jul	-16.2	-29.5	-30.6	-7.5	-19.1	-15.7
Aug	-19.0	-37.3	-40.4	-12.1	-21.9	-20.0
Sep	-23.4	-41.8	-43.5	-9.2	-14.2	-14.2
Oct	-24.3	-41.8	-44.6	5.6	-2.7	2.0
Nov	-34.0	-42.6	-45.4	4.7	0.9	6.0
Dec	-37.4	-39.7	-41.8	12.7	8.9	16.6

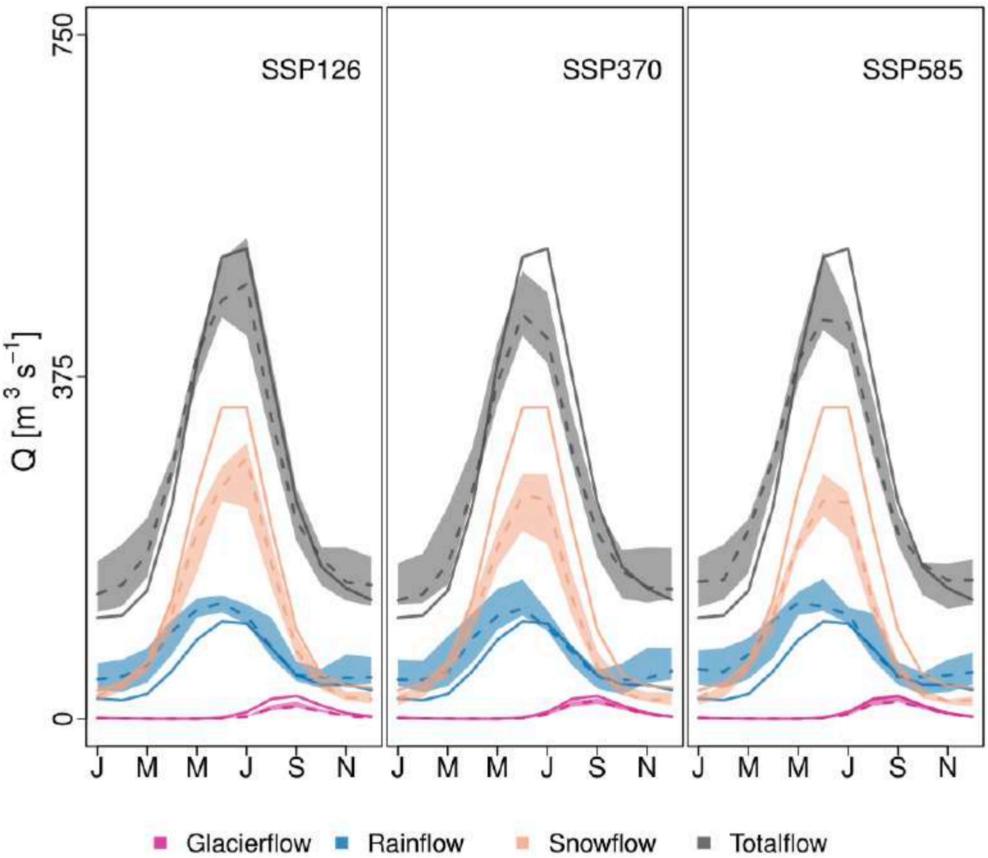


Figure 8. Seasonal changes in the hydrological regime for the mid-century (2036–2065) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The panels represent three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585. The shaded color represents the variability (minimum and maximum) of the flow contributors. The dashed and solid colored line represents the median of the five climate models and baseline flow (1991-2020).

Box 4: Seasonal changes in the hydrological regime for mid-century (2036 to 2065)

Snow melt runoff decreases ↓ due to warming and less snowfall. The decline is higher for SSP585 compared to SSP126 and SSP370.

Rainfall runoff contribution increases ↑ due increase in liquid precipitation (i.e., rainfall).

The **total flow** decreases ↓ during the summer months (June to October).

The increasing ↑ contribution of rainfall-runoff and the decreasing ↓ contribution of glacier and snow runoff are the prime reasons for the detected **shift in peak total runoff** from **July to June** ← for mid-century.

From 2071 to 2100

For the end-of-century time slice, more extreme changes are observed (Table 4 and Figure 9). The magnitude of the change is higher for SSP585 compared to SSP126. The rainfall-runoff contribution intensifies compared to the mid-century for all the SSPs. The snow runoff reduces significantly compared to the baseline for the end-of-century (Box 5). The snowmelt runoff in September reduces to approximately 63% for SSP370 and 75% compared to baseline for SSP585 (Table 4). The reduction in snow flow runoff is higher by the end-of-century compared to the mid-century (Table 3 and Table 4). The reduction is mostly due to elevated warming by the end-of-century time horizon (Figure 57).

Table 4. Climatological changes (expressed as % compared to the baseline flow) in the snow and total runoff for the end of century (2071–2100) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan).

	Snow melt runoff			Total runoff		
	SSP126	SSP370	SSP585	SSP126	SSP370	SSP585
Jan	-21.6	-25.4	-22.3	15.7	28.2	40.6
Feb	-13.3	-3.1	-4.2	25.2	37.0	49.8
Mar	-13.4	4.0	7.7	28.0	41.4	57.5
Apr	-21.4	-12.5	0.5	10.5	20.9	41.7
May	-22.8	-27.0	-23.3	-2.9	2.4	1.2
Jun	-25.5	-37.1	-45.5	-12.8	-14.1	-25.2
Jul	-27.0	-46.7	-61.4	-18.1	-32.7	-41.6
Aug	-30.8	-58.4	-71.8	-17.7	-36.6	-42.4
Sep	-33.9	-62.3	-74.9	-13.9	-31.4	-33.5
Oct	-28.0	-62.1	-72.2	-0.9	-18.1	-17.9
Nov	-33.6	-54.4	-65.0	5.5	-6.3	-2.7
Dec	-39.7	-40.4	-52.2	7.7	5.4	21.9

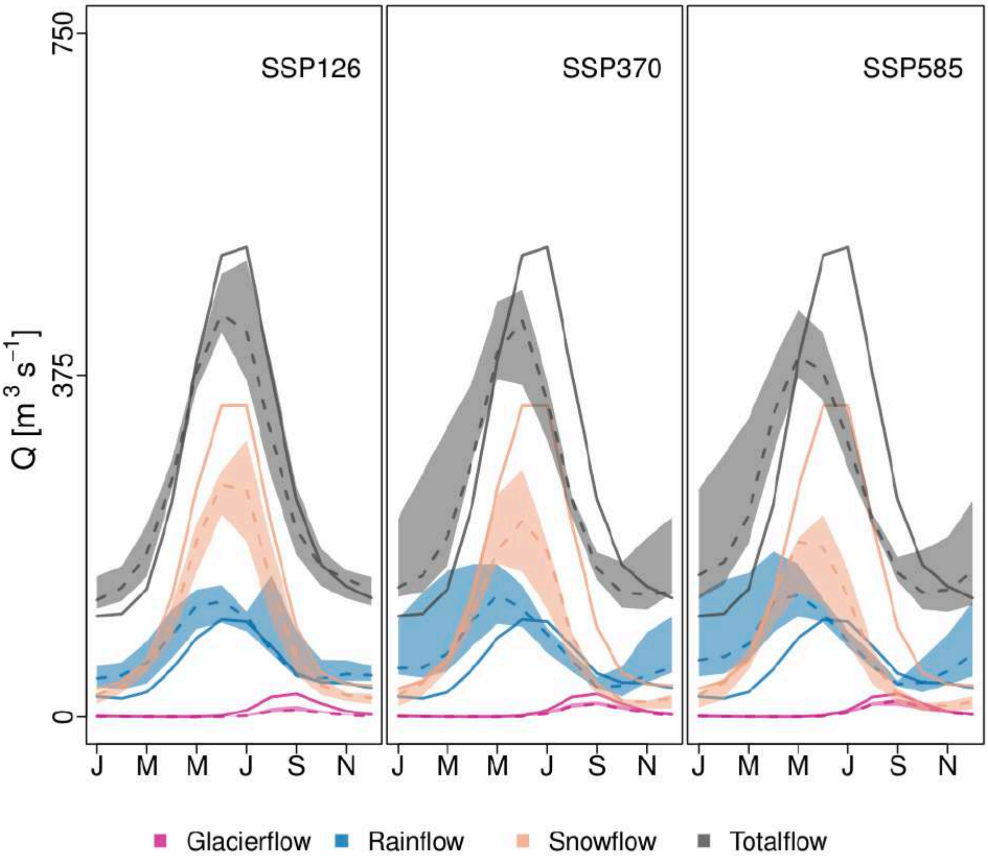


Figure 9. Seasonal changes in the hydrological regime for the end of century (2071–2100) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The panels represent three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585. The shaded color represents the variability (minimum and maximum) of the flow contributors. The dashed and solid colored line represents the median of the five climate models and baseline flow (1991-2020).

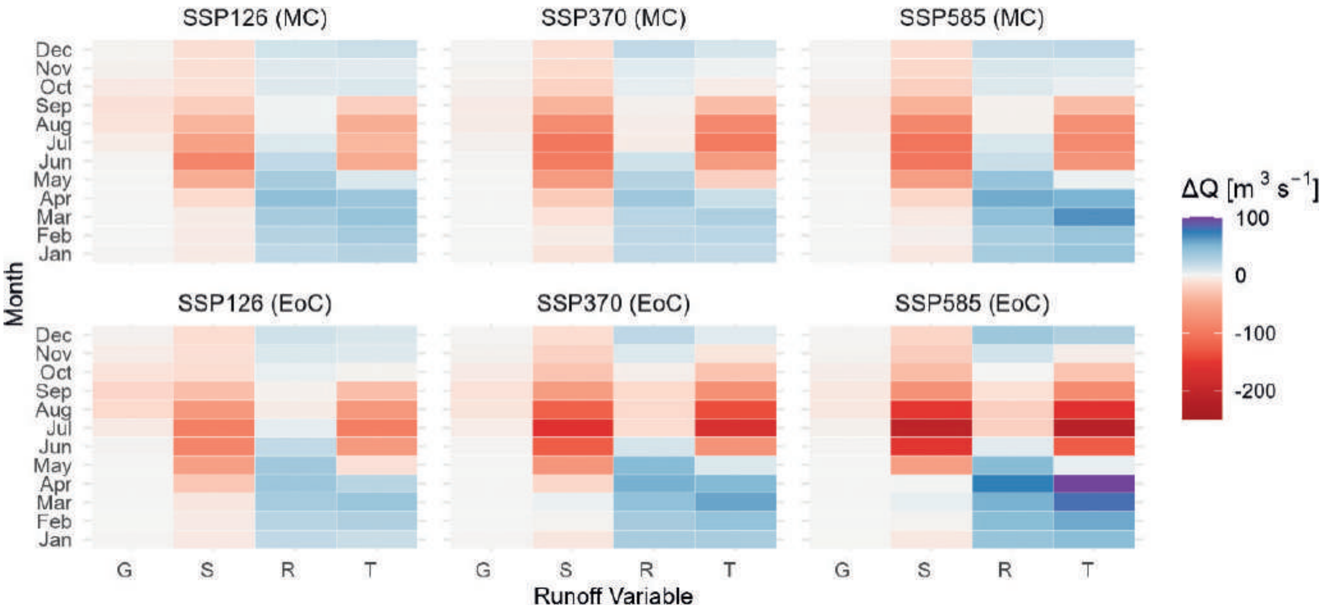


Figure 10. Absolute long term monthly changes in the hydrological regime for the mid-century (MC, 2036–2065, top row) and the end of century (EoC, 2071–2100, bottom row) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The six panels represent three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585 for each time horizon. The color represents the absolute change in the median of the five climate models compared to baseline flow (1991-2020) for different runoff variables (G for glacier, S for Snow, R for rainfall-runoff and T for total flow).

The total runoff magnitude decreases significantly and the shift in the peak total runoff becomes more evident by the end-of-century for SSP370 and SSP585 scenarios. The long-term average peak total runoff for the SSP370 scenario reduces by ~15.6% and shifts from July to June by the end of century (Table 5). Whereas the reduction is larger in magnitude, i.e., ~23.3%, and the average peak total runoff timing shifts from July to May for SSP585 scenario by the end of century.

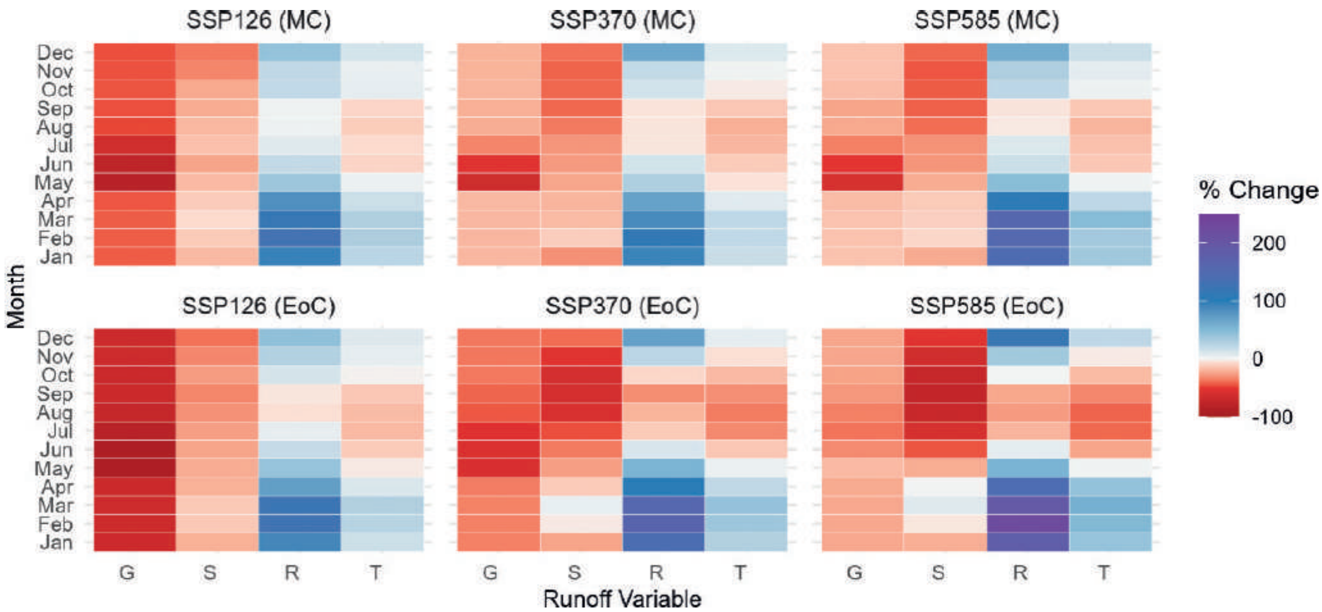


Figure 11. Long-term monthly in the hydrological regime for the mid-century (MC, 2036–2065, top row) and the end of century (EoC, 2071–2100, bottom row) at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The six panels represent three Shared Socioeconomic Pathways, i.e., SSP126, SSP370 and SSP585 for each time horizon. The color represents the % change in the median of the five climate models compared to baseline flow (1991-2020) for different runoff variables (G for glacier, S for Snow, R for rainfall-runoff and T for total flow).

The seasonal changes, i.e., reduction in magnitude of total flow and shift in the peak total flow, will significantly impact the downstream water users (Box 4 and Box 5). In particular, the small and medium-hold farmers in the mountains (along Matcha and Fondarya sub-basin) will be vulnerable to these seasonal changes. **The farmers may need to shift the crop type and cropping pattern to cater for consequences of snowmelt driven regime to rainfall runoff regime.**

Table 5. Reduction in the peak flow of the contributors (G for glacier, S for Snow and R for rainfall-runoff) and total flow (T) expressed as % at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The '-' value indicates the decrease and + increase in peak flow.

		G	R	S	T	Shift in peak total runoff
MC	SSP126	-46.4	+19.1	-16.2	-7.5	July to July
	SSP370	-21.9	+13.5	-28.3	-14.0	July to June
	SSP585	-25.5	+19.3	-30.0	-15.2	July to June
EoC	SSP126	-69.4	+18.4	-25.5	-14.3	July to June
	SSP370	-42.3	+25.5	-37.1	-15.6	July to June
	SSP585	-29.1	+25.8	-43.7	-23.3	July to May

Box 5: Seasonal changes in the hydrological regime for end of century (2071 to 2100)

For the end-of-century time slice, more **extreme changes** are observed compared to mid-century.

Snow melt runoff decreases ↓ due warming and less snowfall. The decline is higher for SSP585 compared to SSP126 and SSP370.

Rainfall runoff contribution increases ↑ due increase in liquid precipitation (i.e., rainfall).

The **total flow** decreases ↓ during the summer months (June to November).

The increasing ↑ contribution of rainfall-runoff and the decreasing ↓ contribution of glacier and snow runoff are the prime reasons for the detected **shift in peak total runoff**

Annual and decadal changes

For the annual scale, snow and glacier melt runoff show a clear declining trend by the end of century (Figure 12). The rainfall-runoff and baseflow components increase in the future. This increase is attributed to the increased liquid component of the precipitation (i.e., Rainfall) in the ZRB. The increase in rainfall-runoff and baseflow components is leveled off by the decline in the snow and glacier melt runoff.

By the end of century, the annual snow melt runoff is projected to decrease significantly, with the most pronounced decline occurring under the SSP585 scenario, where it is expected to drop by approximately 49% compared to initial conditions (2031) (Table 6). This substantial reduction in snow melt runoff is partially offset by an increase in rainfall runoff, which is projected to rise by ~12% under the SSP370 and SSP585 scenarios.

Despite this increase, the overall trend indicates a decline in total annual runoff for all SSP scenarios. The decline is most significant under the SSP585 scenario, with a total annual runoff decrease of approximately 16%, compared to a decrease of about 11% under the SSP126 scenario.

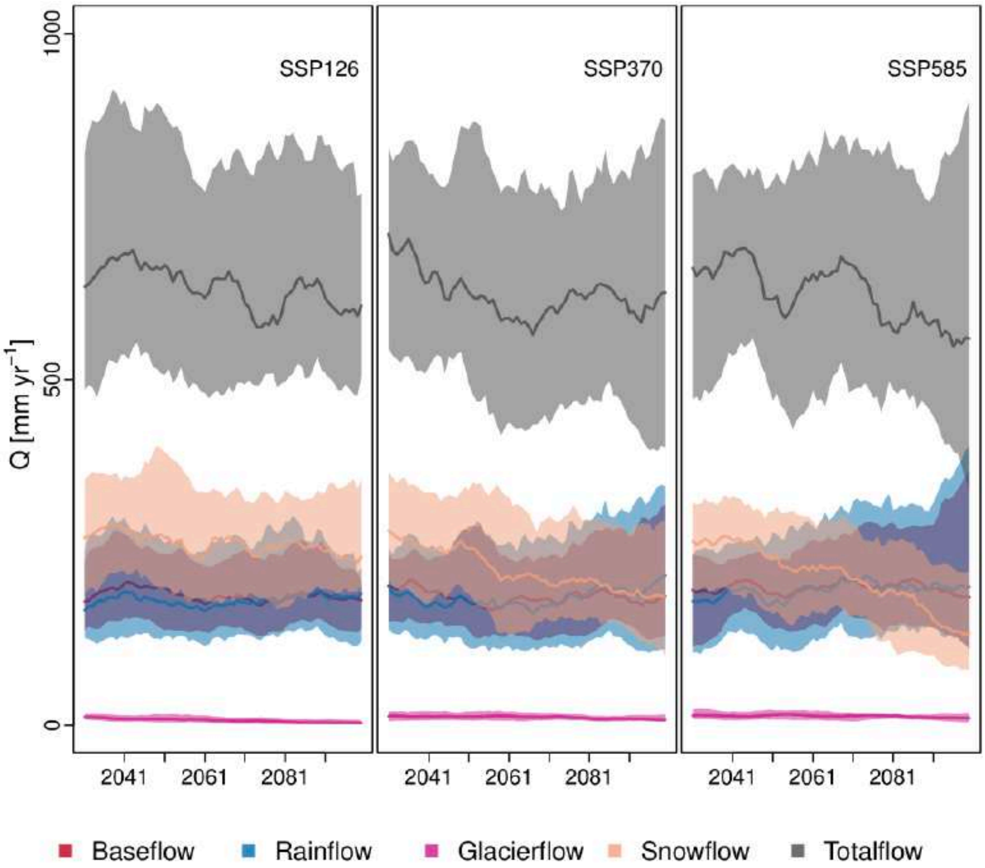


Figure 12. Annual changes in the hydrological fluxes at the outlet of the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The shaded color represents the variability (10-year running mean) of the median flow contributors from five climate models for 2031-2100. The solid-colored line represents the median of five climate models.

Table 6. Reduction in the long-term annual flow (2031-2100) components expressed as % at the outlet of the ZRB (just before the Zarafshon River enters Uzbekistan). The '-' value indicates the decrease and + increase in flow.

	SSP126	SSP370	SSP585
Rainfall runoff	+4.9	+12.2	+11.6
Snow melt runoff	-12.6	-34.4	-49.1
Total runoff	-10.7	-9.4	-16.3

Box 6: Annual and decadal changes in the hydrological regime of Zarafshon River Basin

Snow melt runoff is expected to decrease ↓ under all the SSP scenarios. The SSP585 scenario projects the largest decrease, with a reduction of 49.1% by the end of the century compared to initial conditions (2031).

Rainfall runoff is projected to increases ↑ under all scenarios, with the SSP370 scenario showing the highest increase at 12.2%.

Despite the increase in rainfall runoff, the **total annual runoff** is expected to decline ↓ under all scenarios. The SSP585 scenario shows the most significant decline in total runoff, with a decrease of 16.3%.

Thus, the hydrological regime changes from Glacial-Nival (glacier and snow melt dominated) to more snowmelt and rainfall runoff (Nival-Pluvial) dominated regime (Khanal et al., 2021). This shift toward a rainfall-driven river system makes it more vulnerable to extreme events, such as floods during periods of heavy rainfall and droughts during extended dry spells. Such changes have profound implications for the region, potentially affecting agriculture, hydropower generation, and water supply reliability, particularly in a future marked by climate variability and heightened uncertainty (Box 7).

Box 7: Present and the future changes in hydrological regime of Zarafshon River Basin

Present

The Zarafshon River Basin is dominated by snowmelt runoff (53% of total runoff), which peaks in June-July. Baseflow (23.1%) and rainfall-runoff (21.3%) are significant contributors, while glacier melt contributes only 2.6% annually but peaks at ~11% in September. Spatial patterns show higher snow and glacier melt contributions in upstream areas, with glaciers contributing up to 70% in some tributaries. Total runoff has slightly decreased over the past 30 years due to declining snow and glacier melt, driven by rising temperatures. Seasonal trends show increased runoff in spring (early snowmelt) but decreased runoff in summer and autumn.

Future

Glacier and Snowmelt Decline: Glaciers are projected to lose 38.6% to 79.6% of their volume by 2100, depending on the SSP scenario (SSP126 to SSP585). Snowmelt runoff is expected to decrease significantly, with reductions of up to 49% by 2100 under SSP585.

Shift in Hydrological Regime: The basin will transition from a glacier- and snowmelt-dominated (Glacial-Nival) regime to a rainfall- and snowmelt-dominated (Nival-Pluvial) regime. Rainfall-runoff will increase significantly (up to 12% by 2100), driven by higher liquid precipitation due to warming.

Seasonal and Annual Changes: Peak runoff timing will shift from July to June (mid-century) and even to May by 2100 under SSP585. The total runoff will decrease annually, with the most significant decline under SSP585 (~16% reduction by 2100).

Impacts on Water Resources: Reduced summer flows and earlier peak runoff will challenge water availability for agriculture, particularly for small and medium-hold farmers in upstream areas. The system will become more vulnerable to extreme events, such as floods during heavy rainfall and droughts during dry spells.

2.2 Water Allocation

2.2.1 Baseline

The WEAP water allocation model as described in Annex **A2.2 Water Allocation Modelling using WEAP is used to analyse the current conditions (Baseline) in Zarafshon. This Baseline scenario will be used to explore challenges, opportunities, projections and potential adaptation interventions for the future.** To achieve this, the SPHY (Annex A2.1 SPHY model) and WEAP models are integrated, with outputs from SPHY serving as inputs for the WEAP model. To include weather variations, the model is run for a period of 20 years (2001-2020). Over those 20 years it is assumed that there were no changes/trends in population nor irrigated area nor in the other demands (industry, livestock). The terms introduced after this section are broadly defined, which has led to numerous conflicting conclusions and inaccurate recommendations. To address this, Box 8 outlines and emphasizes key assumptions that will aid in better understanding the results and interpreting similar Tables and Figures.

Box 8: Key definitions in the water allocation realm

Water Demand: the actual amount of water required by one of the four sectors (domestic, irrigation, industry and livestock). Note that the major consumer of water is the natural landscape (evapotranspiration from vegetation), which is covered by the hydrological model SPHY. So, water demand as used here is only water required for mankind (domestic, irrigation, industry and livestock). This is also sometimes referred to as "blue water".

Delivered: the actual amount of water delivered to the four sectors. This is in most cases lower than the Water Demand, as it is constraint by (i) water availability and/or (ii) water accessibility. So, this is the amount that actually reaches the end water user.

Shortage: also called Unmet Demand simply the difference between Water Demand and Delivered.

Coverage: the ratio between Water Demand and Delivered,

Consumed: the amount of water that is actually used. The difference between Delivered and Consumed is sometimes wrongly referred to as "losses". In most cases this water returns back to the river and/or is used by downstream users.

Water Resources: is the total runoff (including base flow) to rivers and stream available to be used. Sometimes referred to as "blue water". Note that Water Resources are not same as rainfall; substantial amount of water is often consumed (evaporated) by natural landscape.

Outflow: is the amount of water leaving the Zarafshon catchment and flowing downstream.

Based on above one can determine the water balance (for the blue water): Water availability is determined by the hydrological processes as modelled by the SPHY model. The accessibility is determined by the data that was available on canal and pumping capacity (Box 9). For each aggregated Jamoat this accessibility was determined by looking at total demand and total supply capacity (by canals and by pumping) based on data provided by the local stakeholders and water users.

Box 9: Water Availability vs. Water Accessibility

In water resources, the distinction between water availability and water accessibility is critical for understanding the dynamics of water resources management. Water availability refers to the quantity of water present in a region, encompassing both surface and groundwater resources, quantifiable in cubic meters (m^3). It is determined by natural hydrological processes, including precipitation, evaporation, and runoff, and can be influenced by climate change and variability.

On the other hand, water accessibility is a measure of the ease with which humanity can obtain water, considering both physical and economic factors. Accessibility is not solely a function of the presence of water but also of the infrastructure (i.e., pipes, pumps, treatment facilities) and governance systems (i.e., policies, regulations, distribution mechanisms) that allow for its extraction, treatment, and delivery to end-users. While a region may have high water availability, if the infrastructure or governance systems are inadequate, the accessibility of that water to the population may be low. This distinction is crucial for effective water resources management, highlighting the need for integrated approaches that consider both hydrological and socio-economic factors to ensure sustainable water supply and equitable access.

Access to water can also be significantly hindered by the proximity of users to water sources. In many regions, water sources can be kilometers away. The large-scale distribution of water through pumps and transmission canals is a critical infrastructure component that enables access to water across considerable distances. However, the efficiency of these systems is contingent on advanced engineering and substantial energy inputs. Transporting water over large distances requires significant energy, often derived from non-renewable sources, thus impacting the environment, and entailing high operational costs. They also introduce challenges related to sustainability, maintenance, and resource management.

Key results are presented in the Figures and Tables below. Table 7 and Figure 13 show clearly that **the total amount of water available ("water resources") is much higher compared to the total water demand. Of the total water resources available from upstream inflows and from runoff in the catchment itself, about 2% is the withdrawal demand. Of this withdrawal demand, not everything is delivered since there are restriction in the supply system (canals, pumping stations, maintenance, capacity of pipes, amongst others).**

Table 7. Average annual water components (2001-2020) for the entire Zarafshon catchment for the current situation based on the WEAP water allocation model.

	Average 2001-2020 in million cubic meters per year (MCM/y)						
	Water Demand	**Delivered**	**Shortage**	Coverage	Consumed	**Water Resources**	Outflow
Zarafshon River Basin	217	**141**	**76**	65%	110	**9,329**	9,219

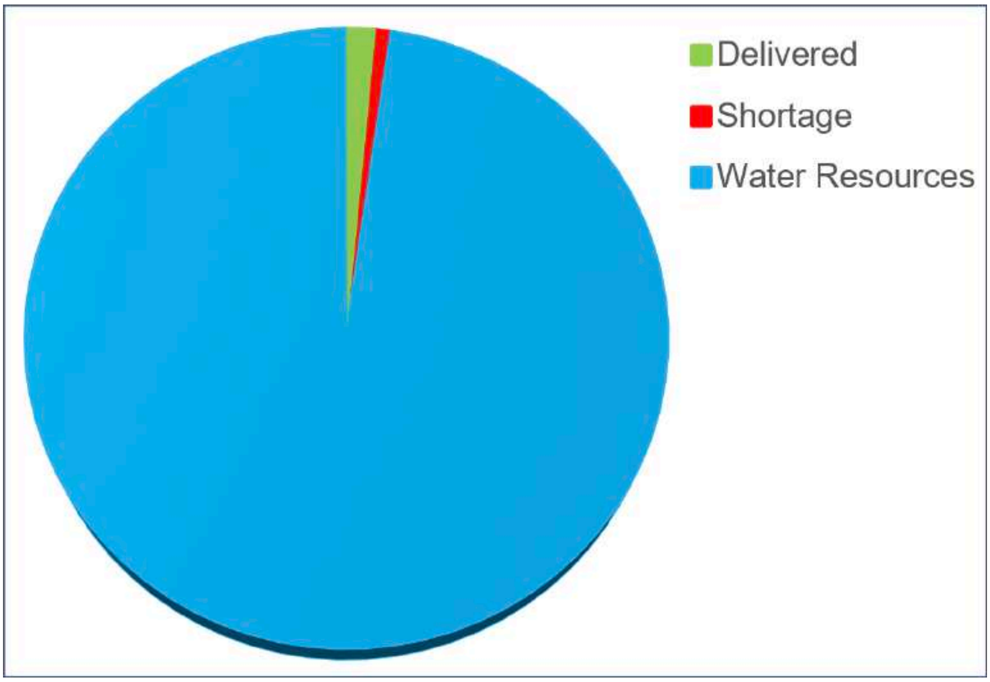


Figure 13. Same information as in Table 7 highlighting that demand (sum of delivered and shortage) is much smaller than the water resources available. Yet there is a significant shortage in water access, the supply infrastructure cannot meet the demand.

Table 8 and Figure 14 presents the same information but now segregated by each demand sector. The irrigation sector is the major water demanding one and where the lack of water access (shortage) is greater compared to other sectors. Figure 15 shows the same information on demand and supply for each of the nine aggregated Jamoats.

Table 8. Average annual water components (2001-2020) for the entire Zarafshon catchment for the current situation based on the WEAP water allocation model. Here separated per water demand sector.

	Average 2001-2020 in million cubic meters per year (MCM/y)				
	Water Demand	**Delivered**	**Shortage**	Coverage	Consumed
Domestic	8	**5**	**3**	66%	3
Industry	15	**9**	**6**	61%	5
Irrigation	187	**122**	**65**	65%	98
Livestock	7	**5**	**2**	65%	4
Sum	**217**	**141**	**76**	**65%**	**110**

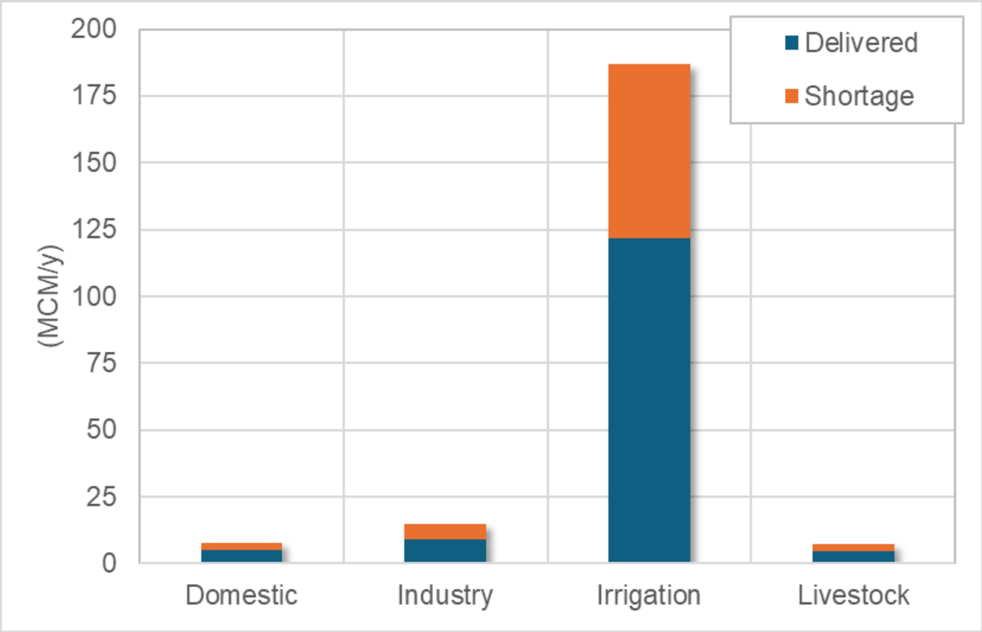


Figure 14. Same information as in Table 8 showing that demand for the irrigation sector is dominant compared to the other sectors. Also, the substantial water shortage due to lack of sufficient effective water supply infrastructure.

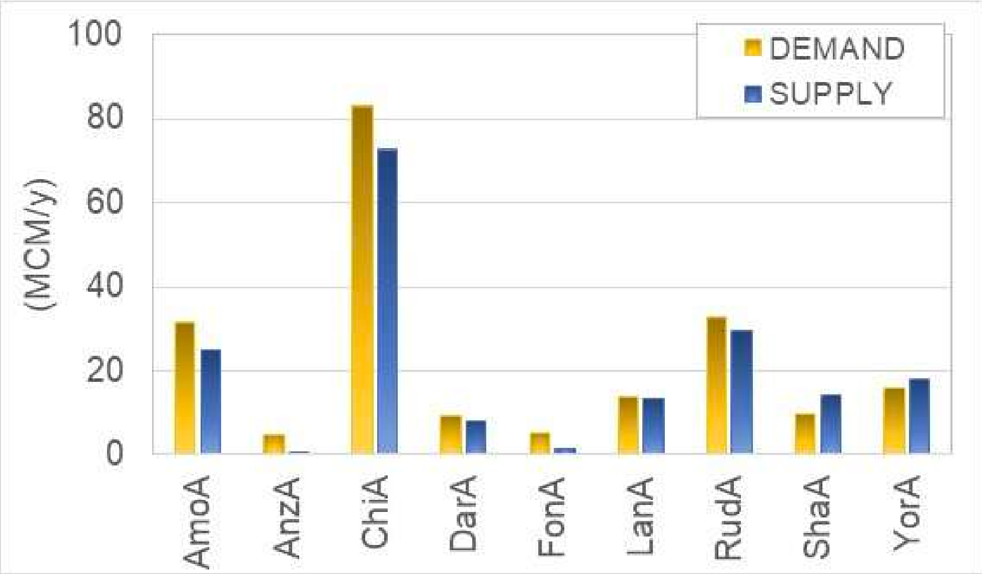


Figure 15. Total water demand and the water supply capacity for each of the aggregated Jamoats.

Considering a relatively dry year (defined as the year with the lowest water availability in the period 2001-2020) shortages (unmet demand) are much higher compared to the average year (Figure 16). Table 9 shows for this dry year that coverage is 48% of water demand, while for an average year (Table 7) this is 65%. **This decrease in coverage is not caused by water resource availability (although it goes down by 24%) but by the higher water demand and the supply delivery system (canals, pumps, pipes, etc) not able to supply this higher demand.**

Table 9. Annual water components for a dry year (2006) for the four demand sectors for the current situation based on the WEAP water

allocation model.

	Dry Year (2006) (MCM/y)						
	Water Demand	Delivered	Shortage	**Coverage**	Consumed	Water Resources	Outflow
Zarafshon River Basin	295	142	153	**48%**	111	7,549	7,437
Difference compared to average	+26%	+1%	+50%	**-35%**	+1%	-24%	-24%

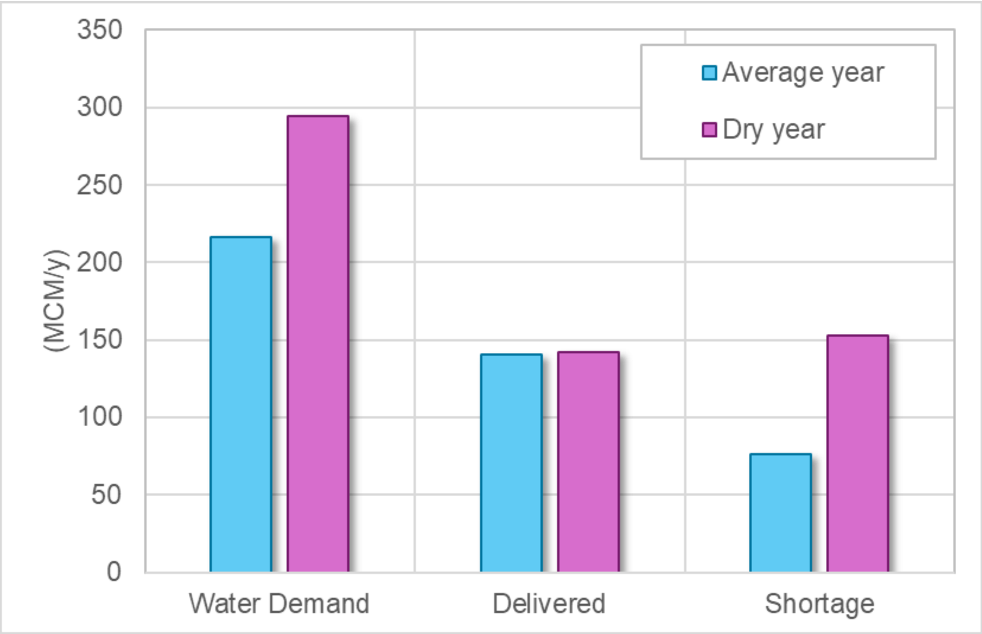


Figure 16. Differences in water demand, delivered and shortage between an average year (2001-2020) and a dry year (2006).

The analysis using the WEAP model as described in Annex A2.2.2 WEAP Water Allocation Model provides an enormous number of results both in spatial as well as temporal resolution. In this section, we present a selection of the most significant results derived from the analysis. It is important to note that the full set of output data is comprehensively included within the WEAP model, where all results are systematically stored and available for further examination.

Figure 17 reflects the graphical results provided by the WEAP water allocation model as plotted by the WEAP GUI. Streamflow shown for Jan-2002 (top) and Jun-2002 (bottom). The thickness of the river shows the streamflow. Numbers are the flows in m3/s. Figure 17 presents a nice feature of the analysing results of the WEAP model. **Streamflow can be presented as thicknesses of the rivers providing a quick overview on changes in streamflow over time and space.** Other outputs from the model, such as water demand and shortages, can be displayed as well. In this Figure, the streamflow in the rivers for two months is shown clearly indicating the **big seasonality.**

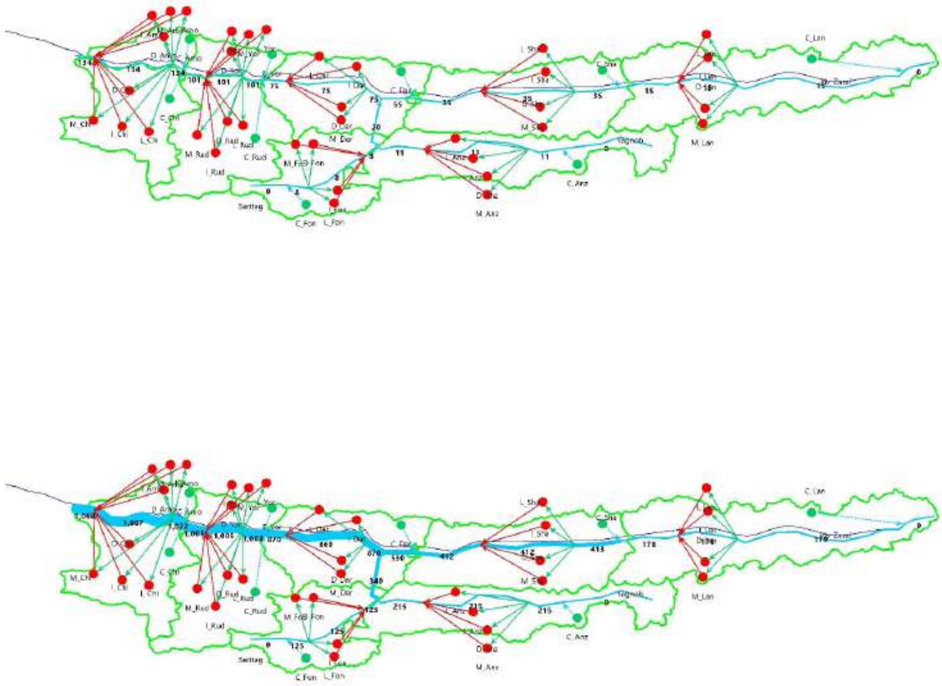
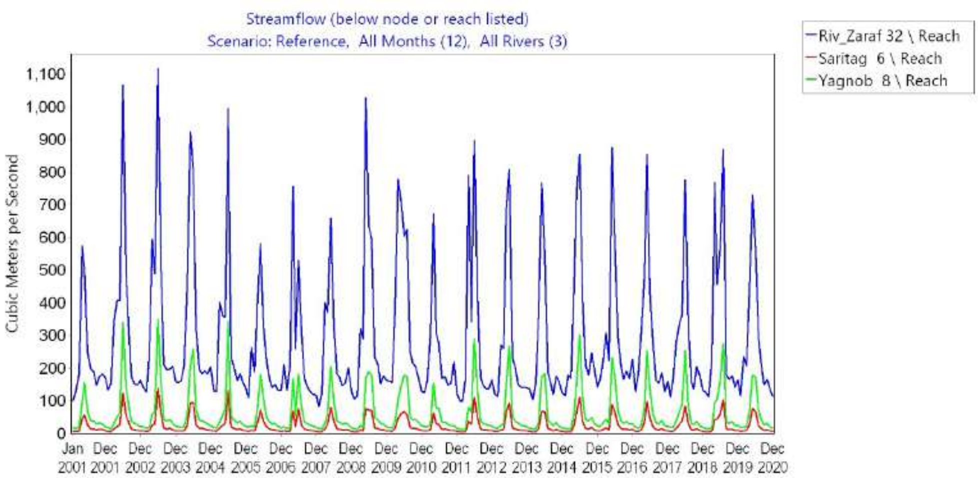
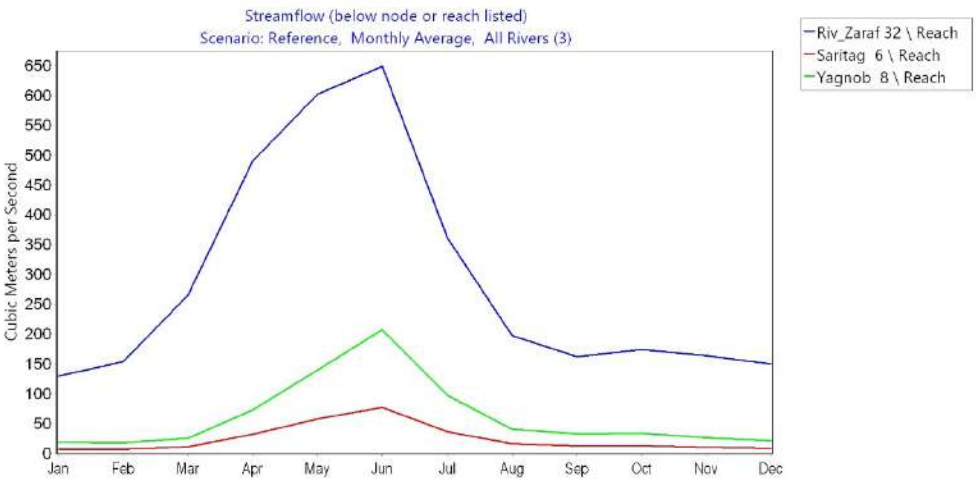


Figure 17. Example of graphical results provided by the WEAP water allocation model as plotted by the WEAP GUI. Streamflow shown for Jan-2002 (top) and Jun-2002 (bottom). The thickness of the river shows the streamflow. Numbers are the flows in m3/s.

Figure 18 demonstrates the ability of the WEAP model to present streamflow in the river aggregated at different temporal scales. Seasonality in the basin can be clearly observed as well as the year-to-year variation. **Note that the flows presented here include human induced abstractions as well, this in contrast of the SPHY model that focuses on getting water resources as accurate as possible.**





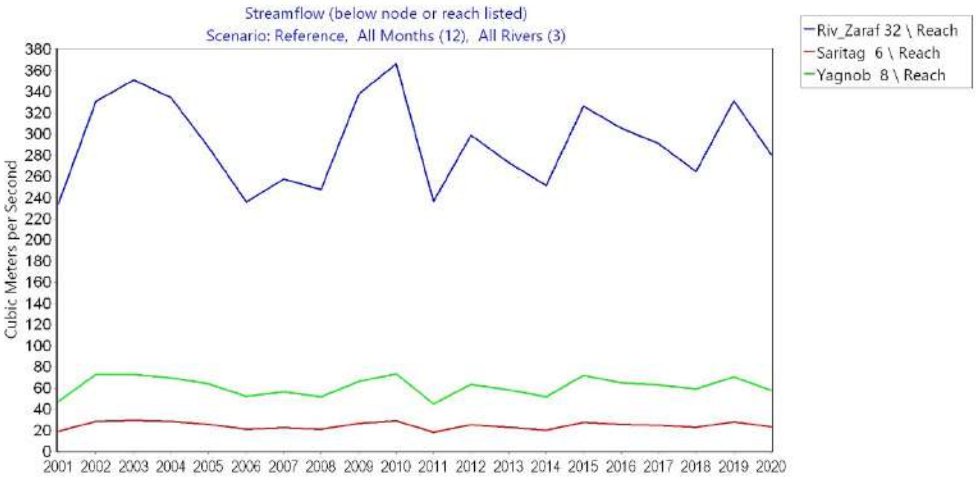
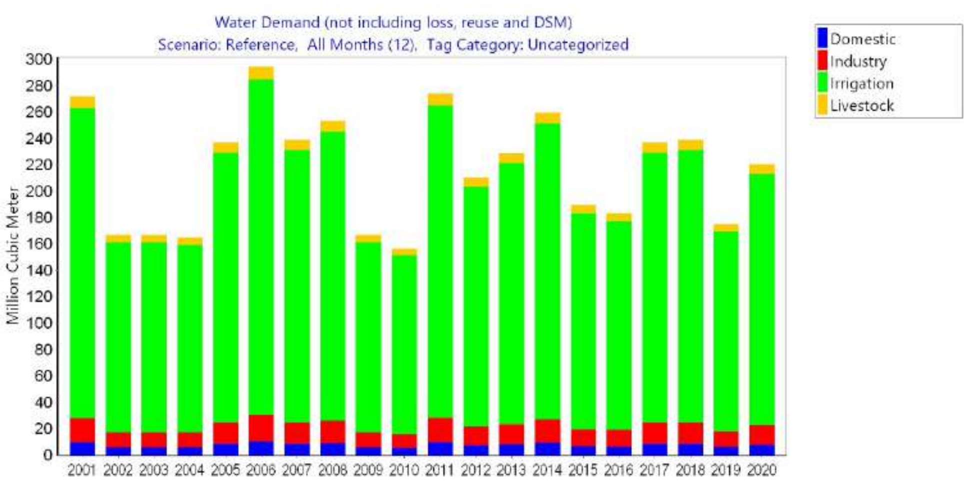


Figure 18. Streamflow in m3/s for the three main rivers at their outlet points as plotted by the WEAP GUI. Monthly for all years, average monthly and average yearly. All for the period 2001 to 2020.

Figure 19 and Figure 20 show the ability of the model to present in a clear way the water demand and unmet demand (water shortage) for the four main sectors and for the aggregated Jamoats. **Irrigation is the major abstractor and consumer sector in the basin. Note that for every year water shortage is occurring. As mentioned earlier this is not caused by a lack of water resources, but by an insufficient water supply system.**



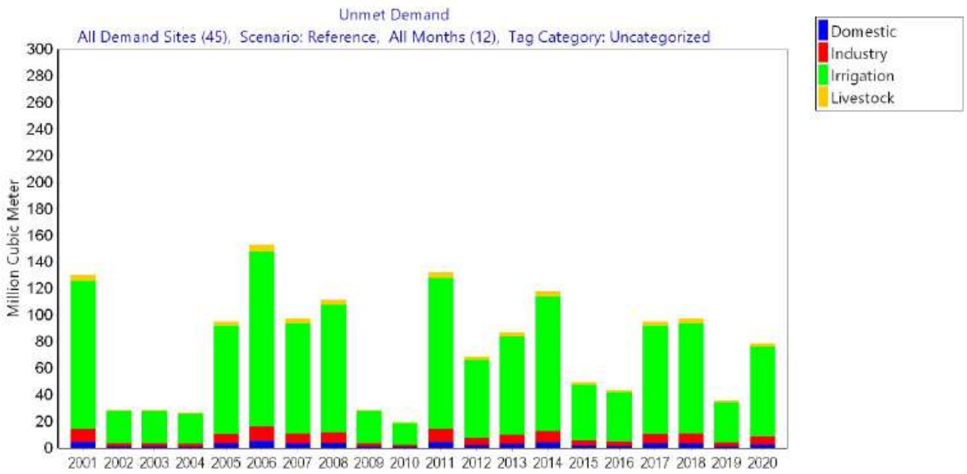


Figure 19. Demand (top) and unmet demand (water shortage) (bottom) per sector as plotted by the WEAP GUI.

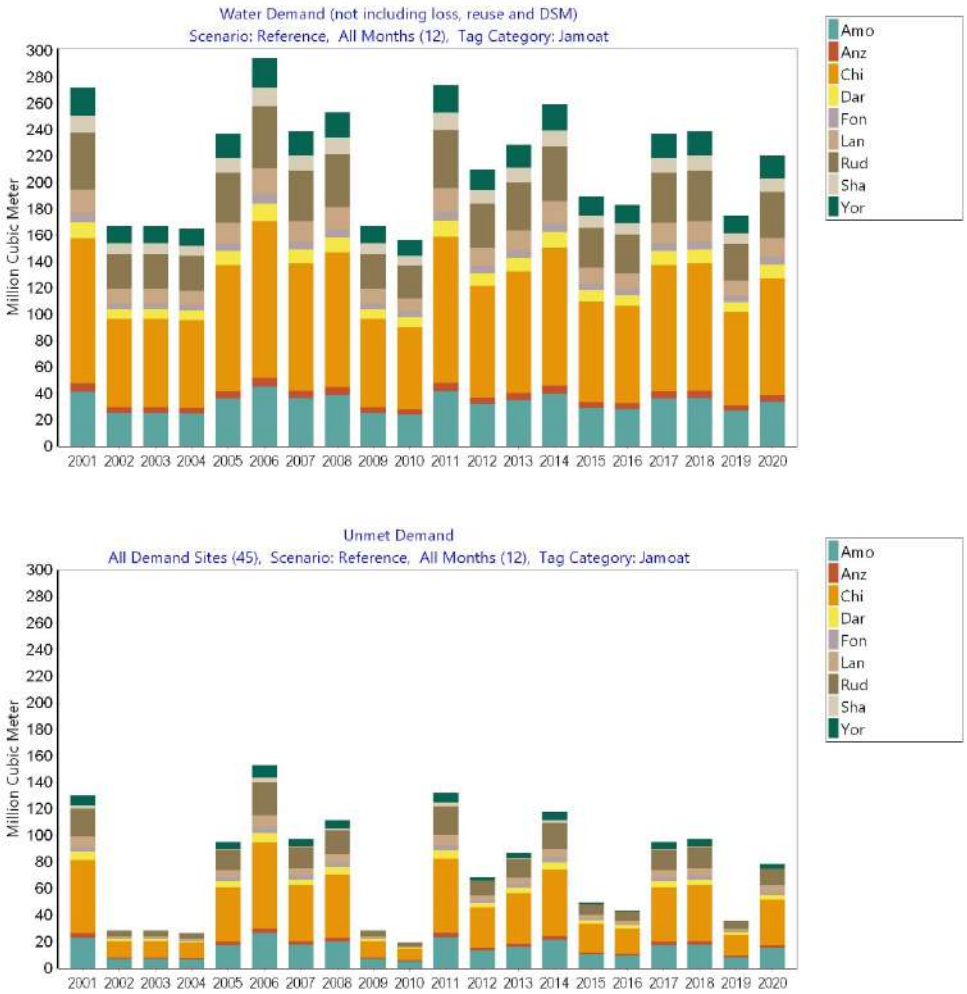


Figure 20. Demand (top) and unmet demand (water shortage) (bottom) per Jamoat as plotted by the WEAP GUI. The bars clearly indicate that for each Jamoat the demand and unmet demand (water shortage) differs.

Based on the previous Tables and Figures, the **main conclusions regarding the baseline for water allocation in the ZRB** are as follows:

Water demand is about 2% of the available water resources (runoff) in the Zarafshon river basin. This means that over **98% of water resources generated on the Tajik side of the Zarafshon transboundary basin flow downstream into Uzbekistan. Water shortage, or better unmet demand, is mainly due to lack of water accessibility,** due to an **insufficient water supply system** (water infrastructure).

Box 10 points at **the lack of maintenance of water infrastructure** as the main driver for the lower levels of water accessibility in Tajikistan. Of the water delivered, this is the water that reaches the water users, about 79% is consumed, while the remaining flows back to the streams. In the case of a dry year, (Table 8 and Table 9) water resources (so runoff and baseflow) can reduce by around 25%. Obviously, water demand will increase but given limitations in the water supply system this additional demand cannot be delivered. So, **although sufficient water resources are available in the Zarafshon river basin, coverage is only 65% during an average year and even lower down to 48% in a dry year.**

Box 10: Maintenance

Maintenance of water infrastructure is a pivotal element in the broader context of integrated water resources management (IWRM), directly impacting the efficiency, cost-effectiveness, and resilience of water systems against the backdrop of global challenges such as urbanization, population growth, and climate change. Maintenance involves routine and preventive measures, including inspection, cleaning, repair, and replacement of infrastructure components such as pipes, pumps, treatment facilities, and reservoirs.

However, maintenance of water infrastructure is a key issue of concern in Tajikistan. Water resources are critically important for the country yet increasingly stressed by climatic variability, aging infrastructure, and growing demands.

Detailed information of maintenance in the Zarafshon region is lacking. In the WEAP model a maintenance factor is included, based on expert knowledge, which represent the overall condition on the water infrastructure system. This factor can be altered when evaluating scenarios.

Maintenance is the biggest bottleneck in Tajikistan. WEAP can be used by updating this maintenance factor if budget is made available by the Tajik authorities and agencies responsible for operating and maintaining water and energy infrastructure. For the base line scenario, a factor of 0.75 was used, which means that the existing infrastructure is working at 75% of its capacity. This can be 75% of the time, or 75% of its maximum capacity, or a mixture of those two.

2.2.2 Sensitivity analysis

Effective water resource management requires a clear understanding of key terminology, as different terms carry distinct meanings that influence planning and decision-making.

Box 11 defines and differentiates critical concepts such as **«Projection»**, **«Intervention»** and

«Scenario» providing a structured framework for analyzing future water resource conditions and management strategies.

Box 11: Useful terminology for analyzing future water resources conditions and management strategies

In the context of water resources, the terms «Projection,» «Intervention,» and «Scenario» have specific meanings and applications. Understanding these terms is crucial for developing effective strategies for managing water resources efficiently.

- A **projection** is a potential future state of a system that is based on a set of assumptions regarding future socio-economic developments, technological advancements, population growth, climate change, amongst others. Projections are typically based on various assumptions about the future. Projections are not directly influenced by water managers or policymakers.
- An **intervention** refers to actions or strategies implemented to influence the outcome of a system's future state (a projection). In the context of water management interventions include policy changes, infrastructure development (such as dams, levees, or water treatment plants, among others), changes in water usage practices, nature-based solutions, or the implementation of new technologies. The goal of interventions is to mitigate negative impacts or to take advantage of potential opportunities. Unlike projections, interventions are within the control of policymakers, water managers, and other stakeholders. They are designed based on the understanding of projections and scenarios to steer the system towards a more desirable outcome.
- A **scenario** is an overarching term that encompasses both projections and interventions. It represents a coherent, internally consistent, and plausible description of a possible future state of the Zarafshon. Scenarios are used to explore the implications of different assumptions about the future, including both those that can be influenced by human actions (interventions) and those that cannot (projections).

In summary, **while projections provide a range of possible future states based on certain assumptions and are not directly alterable by human actions, interventions represent deliberate strategies to influence the future state of a system. Scenarios encompass both projections and potential interventions to provide a comprehensive framework for planning and decision-making in the face of uncertainty.**

Projections

A series of exploratory sensitivity analyses were conducted to assess the impact of key assumptions on projected water allocation. These analyses serve as an initial assessment and can be refined or expanded based on specific user requirements (i.e., MEWR or RBC). The projections described below in Box 11 were examined (abbreviations in brackets), providing a structured approach to understanding system behaviour under varying assumptions.

Additional scenarios can be incorporated into the model as needed to further investigate potential impacts. In subsequent sections, a more comprehensive and realistic evaluation will be undertaken by integrating SPHY and WEAP, enabling a detailed assessment of future water availability under scientifically derived climate projections.

Box 12: Future projections analyzed

- **Socio-economic development projection (01_Soci):**
  - Near future (2031–2050): Population, irrigation, industry, livestock: **increase by 25%**
  - Distant future (2061-2080): Population, irrigation, industry, livestock: **increase by 50%**
- **Climate change projection (02_Clim):**
  - Near future (2031–2050): Water resources **reduced by 10%**
  - Distant future (2061-2080): Water resources **reduced by 25%**
- **Combined projection (03_Comb):** Socio-economic development and climate change projections combined

For water allocation modelling, two future time horizons were selected: Near Future (2031–2050) and Distant Future (2061–2080). A 20-year period effectively captures hydrological variability along with the timeframes needed for political decisions and infrastructure development. In this sense, shorter periods (3–5-year simulations) risk missing natural fluctuations, while longer periods (>50 years) might dilute the impact of interventions. The 20-year timeframe enables robust scenario analysis by averaging conditions over dry, wet, and normal years, ensuring that short-term fluctuations don't lead to misleading conclusions about an intervention's effectiveness.

Box 13: Example illustrating why short-term simulations are not suitable for scenario comparisons.

Suppose an intervention is gradually implemented starting in 2031, and 2031 happens to be an exceptionally dry year. Since the intervention is incomplete in that year, short term analysis might misleadingly suggest that the intervention is ineffective. In contrast, a long-term analysis ensures that the full implementation period is considered, providing a more reliable assessment of the intervention's effectiveness across different hydrological conditions.

It is important to note that the first two projection scenarios are somewhat hypothetical, as it is improbable that future conditions will be driven solely by either socio-economic or climate changes in isolation. However, these projections have been incorporated to improve the understanding of the sensitivity of the assumptions and to provide deeper insights into the individual impacts.

Utilizing the WEAP model as described in Annex A2.2.2 WEAP Water Allocation Model, and incorporating the projection scenarios described above alongside the current baseline conditions outlined in the previous section, generates a substantial volume of results with high spatial and temporal resolution. In this section, we present a selection of the most significant outputs. For further detailed analysis, the complete output database remains as included in the WEAP model attached to this report.

Table 10 and Figure 21 reflect the same information in table and graph formats, respectively, regarding the summary of the impacts of those three future projections on Water Demand, Water Supply and Unmet Demand (water shortage). As mentioned above, the first two projections (01_Soci and 02_Clim) are assumed to occur in isolation. For the Climate change projection, it is only assumed to have an impact on water resources (water availability) and not on water demand. Similarly, under the Socio-Economic projection (01_Soci) only changes in demand are considered and streamflow is assumed to be similar as it is currently.

Table 10. Average annual water components for the entire Zarafshon catchment for the various projections and time horizons based on the WEAP water allocation model.

Water components	Projections	Baseline and Time Horizons				
		Current (MCM/y)	Near Future (MCM/y)	Distant Future (MCM/y)	Near Future (MCM/y)	Distant Future (MCM/y)
Water Demand	01_Soci	217	271	325	+25%	+50%
	02_Clim	217	217	217	0%	0%
	03_Comb	217	271	325	+25%	+50%
Water Supply	01_Soci	141	142	142	+1%	+1%
	02_Clim	141	141	141	0%	0%
	03_Comb	141	142	142	+1%	+1%
Unmet Demand	01_Soci	76	129	183	**+70%**	**+141%**
	02_Clim	76	76	76	**+0%**	**0%**
	03_Comb	76	129	183	**+70%**	**+141%**

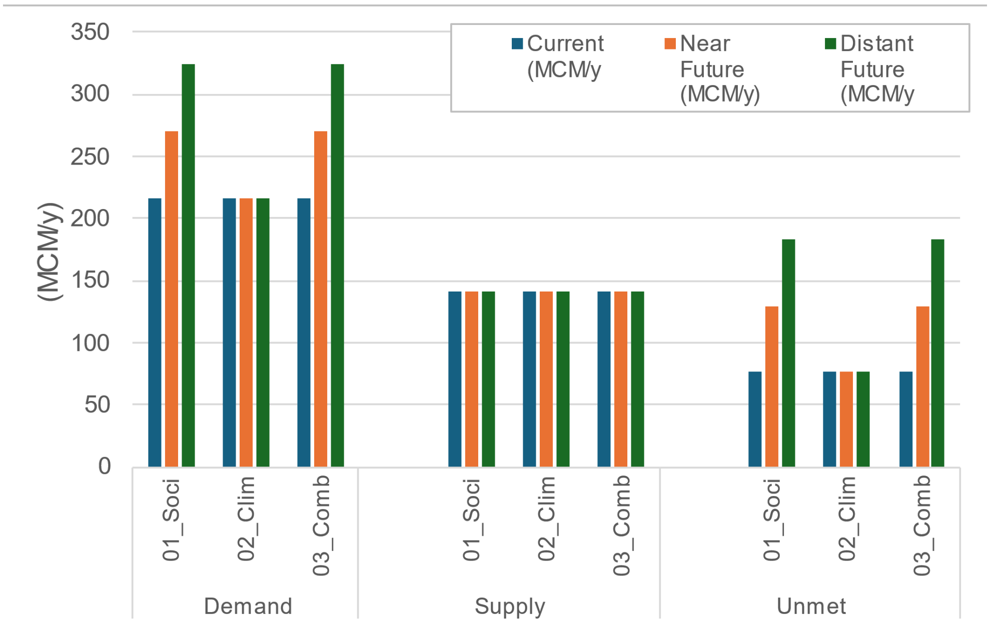


Figure 21. Same information as shown in Table 10

Figure 22 represents the moving average trends in supply and demand for the combined (03_ Comb) projection. **The unmet demand will increase by 4.5 times by 2080, compared to 2020, if the current infrastructure model and lack of maintenance remain.**

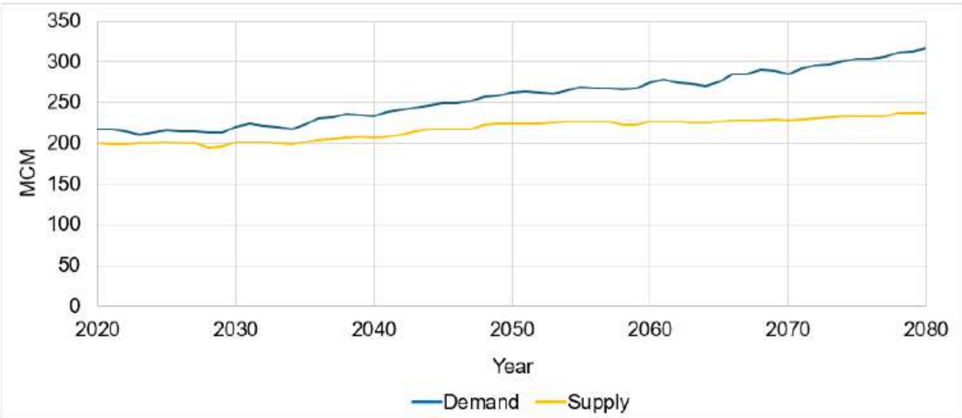


Figure 22. Demand and supply moving average trends (25 years running mean) in MCM for the 03_Comb scenario

Table 11 and Figure 23 reflect the same information in table and graph formats, and demonstrate that under the Socio-Economic projection only, there are no changes in water resources availability.

Table 11. Average annual water resources (runoff) and outflow for the entire Zarafshon catchment for the various projections and time horizons based on the WEAP water allocation model.

	Projections	Baseline and Time Horizons				
		Current (MCM/y)	Near Future (MCM/y)	Distant Future (MCM/y)	Near Future (% change)	Distant Future (% change)
Water Resources Availability	01_Soci	9,329	9,329	9,329	**0%**	**0%**
	02_Clim	9,329	8,396	6,997	**-10%**	**-25%**
	03_Comb	9,329	8,396	6,997	-10%	-25%
Outflow	01_Soci	9,219	9,218	9,218	**0%**	**0%**
	02_Clim	9,219	8,286	6,887	**-10%**	**-25%**
	03_Comb	9,219	8,285	6,886	-10%	-25%

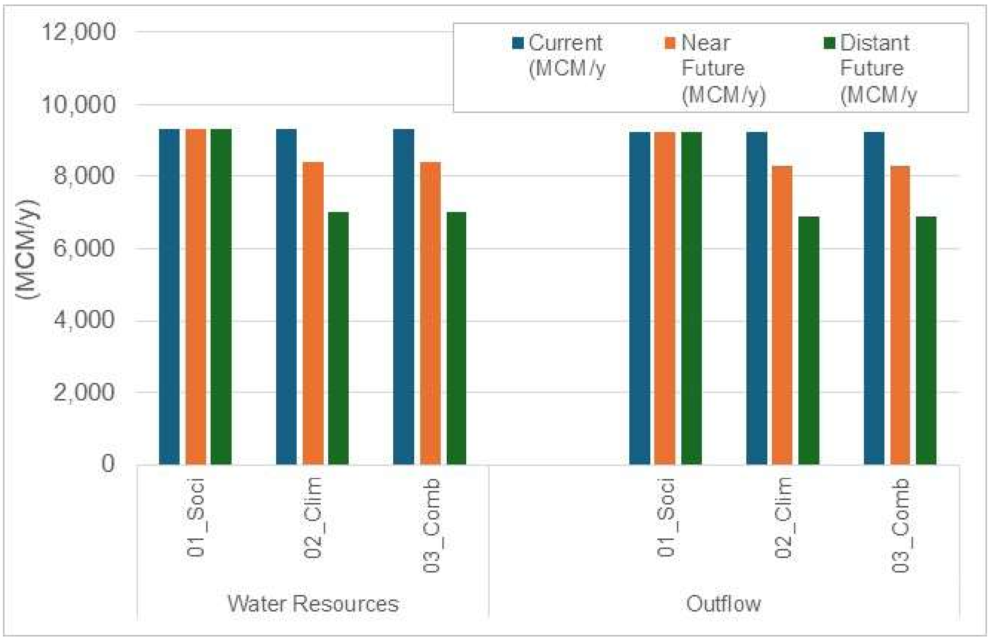


Figure 23. Same information as shown in Table 11.

The **most important observations that can be concluded** from the Tables and Figures above, regarding the impact of those **future projections** can be summarized as follows[7]

Water shortage (unmet demand) will increase substantially under the socio-economic development projection (01_Soci) and the combined (03_Comb) projection, however it will not change under the climate change projection (01_Clim), even though water resources availability decreases substantially.

The critical challenge within the ZRB area is not the overall availability of water resources, but rather the accessibility and effective distribution of these resources. Therefore, the supply is the same under all projections.

Interventions

As concluded from the previous section, **the major water allocation issue in the ZRB is water accessibility. Even under the most extreme projection (combined effect of socio-economic development and climate change) sufficient water is available, but not accessible.**

The interventions described below in Box 14 were explored (abbreviations in brackets).

Box 14: Future Interventions analysed

- **Maintenance Upgrade (04_Main):** In the base line (current situation) the level of maintenance was set at 75%. Under this intervention it is assumed that maintenance level will be increase to 90%
- **Supply Expansion (05_Supp):** The expansion of water supply infrastructure (pumps, canals, etc) was assumed to increase by 50%.
- **Full (06_Comb):** The two interventions, Maintenance Upgrade and Supply Expansion, are implemented both.

It is important to note that the percentages used in these future interventions are not derived from empirical data but are instead based on expert judgment and informed assumptions. These estimates are intended to provide a starting point for exploration rather than definitive values. Should more accurate and validated data become available, the intervention parameters can be refined accordingly to enhance the reliability of the projections.

The interventions described were applied to the **most extreme Projection (03_Comb).**

Consequently, the interventions presented here should be interpreted as a sensitivity analysis aimed at exploring the range of possible impacts under varying assumptions. This approach allows for a better understanding of the model's response to changes in key variables and serves as a tool for identifying critical areas where future research or data collection efforts should be concentrated.

7 For more detailed output (numbers, tables, charts) the WEAP model itself can be used.

Table 12 and Figure 24 reflect the same information in table and graph formats and present the overall impact of those two interventions on water Demand, Supply and Unmet Demand (water shortage). The Table demonstrates again that **the interventions considered are "supply" intervention and do not assume any changes in demand. The two interventions are very effective in reducing Unmet Demand, although still not sufficient to reduce Unmet Demand to zero.**

Table 12. Average annual water components for the entire Zarafshon catchment for the various interventions and time horizons based on the WEAP water allocation model.

Water components	Projections	Baseline and Time Horizons		
		Current (MCM/y)	Near Future (MCM/y)	Distant Future (MCM/y)
Water Demand	03_Comb	217	271	325
	04_Main	217	271	325
	05_Supp	217	271	325
Water Supply	03_Comb	134	135	136
	04_Main	159	162	162
	05_Supp	184	198	202
Unmet Demand	03_Comb	76	129	183
	04_Main	51	102	155
	05_Supp	24	63	114
Differences (%), compared to 03_Comb				
Water Demand	04_Main	0%	0%	0%
	05_Supp	0%	0%	0%
Water Supply	04_Main	+18%	+19%	+20%
	05_Supp	+37%	+46%	+49%
Unmet Demand	04_Main	-33%	-21%	-15%
	05_Supp	-68%	-51%	-38%

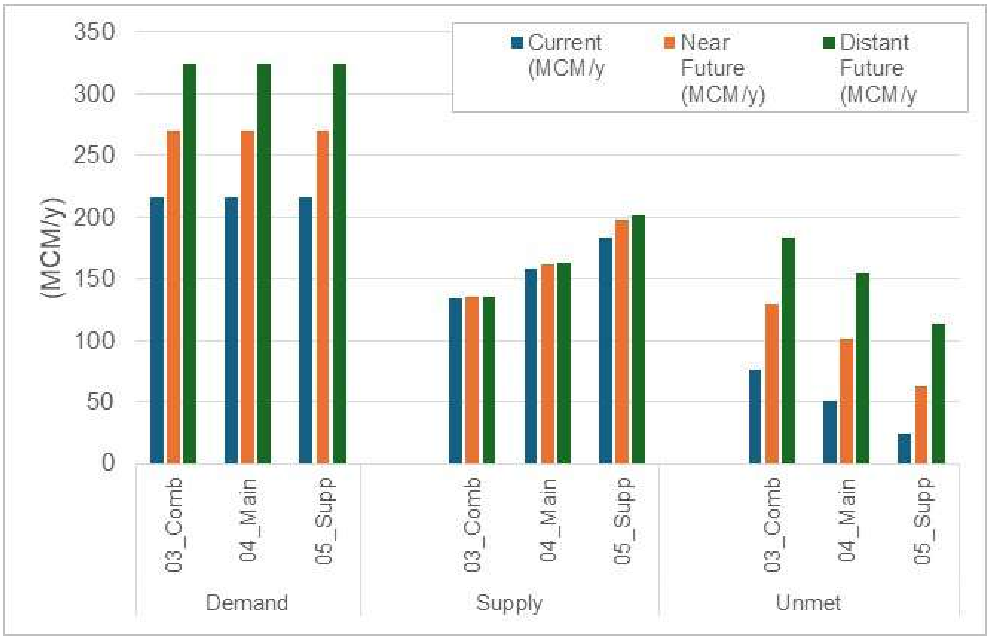
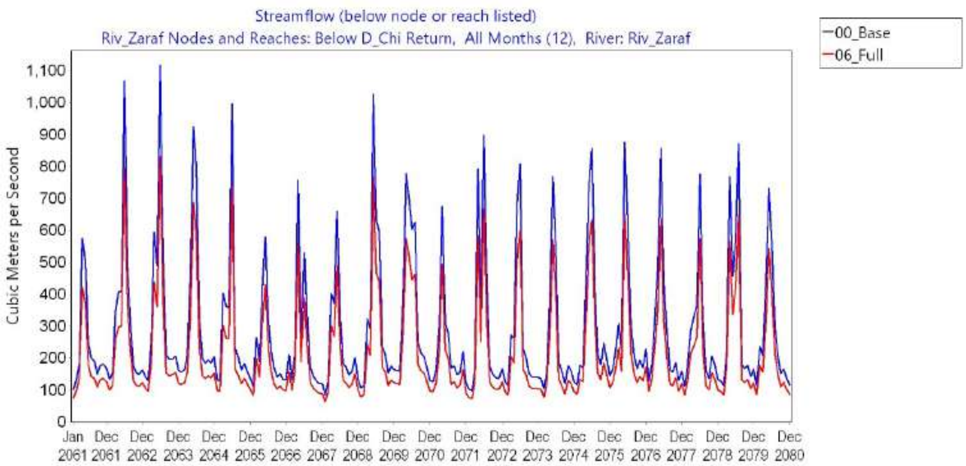
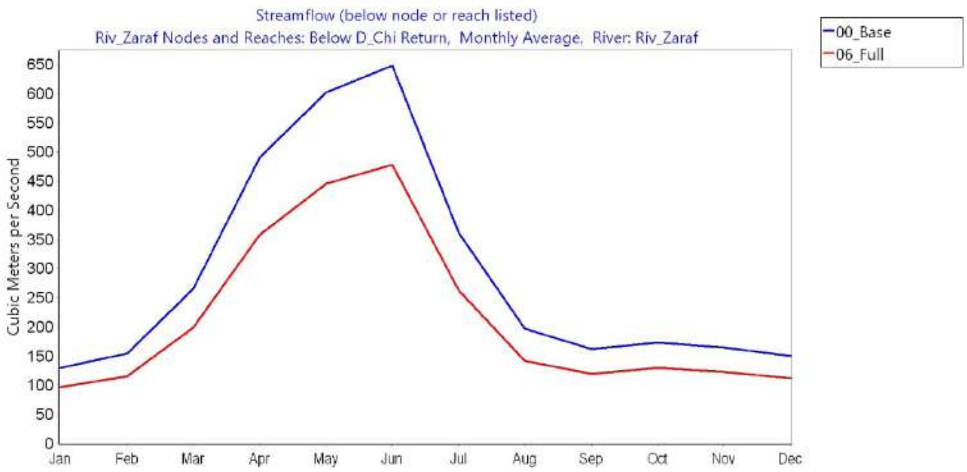


Figure 24. Same information as shown in Table 12

Figure 25 and Figure 26 focus on the effects of the future interventions on river flows. As expected, an increase in supply capacity results in higher water consumption, which subsequently reduces river flows. The figures compare the current flow baseline («00_Base») with the combined projections and intervention scenarios («06_Full»). This includes the cumulative effects of climate change, socio-economic development, increased supply capacity, and improved maintenance. This combined scenario represents the most plausible future development under the given assumptions. **The results indicate a significant reduction in river flows; however, water resources remain abundant and capable of meeting demands under these conditions.**





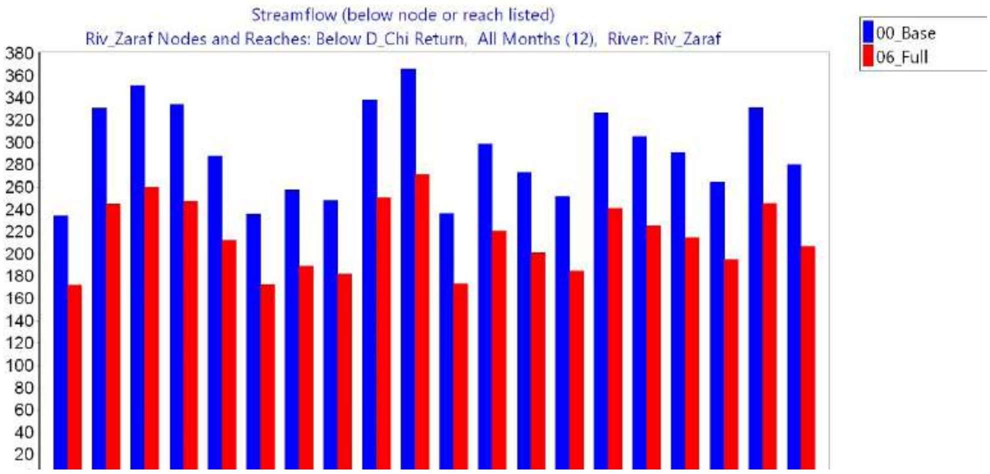


Figure 25. Streamflow in m3/s for the Zarafshon river at its outlet point. Monthly for all years (top), average monthly (middle) and average yearly (bottom). The two scenarios represent the current situation (00_Base) and the scenario that will have the most impact on the streamflow in the river (06_Full).

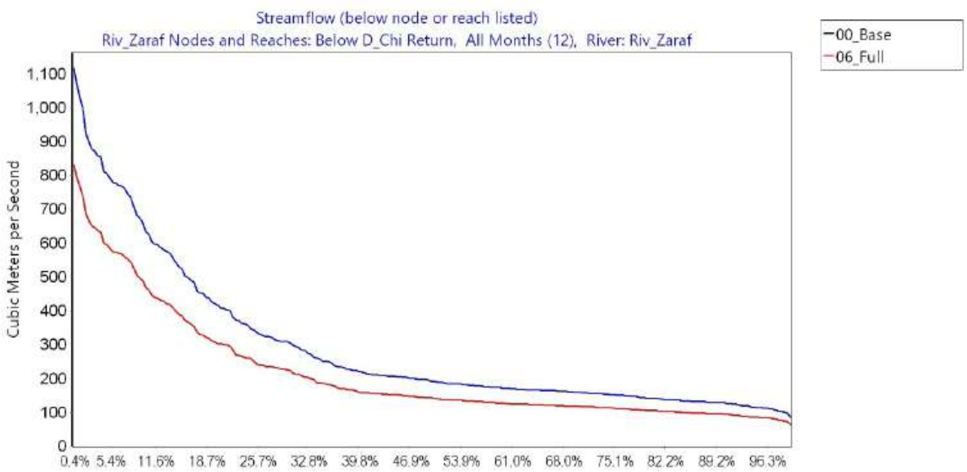


Figure 26. Flow duration curve m3/s for the Zarafshon river at its outlet point. The two scenarios represent the current situation (00_Base) and the scenario that will have the most impact on the streamflow in the river (06_Full).

The **most important observations that can be concluded** from the Tables and Figures above, regarding the impact of those **future interventions** can be summarized as follows:

Water supply will be greatly enhanced by expanding the supply infrastructure and to a certain extent improving maintenance of the existing infrastructure. Unmet demand (water shortage) will decrease substantially under those interventions. Even for the current situation both interventions are beneficial and will enhance water supply and lower unmet demand. The impact of those additional supplies and thus consumption has some impact on stream flows although much lower compared to the impact of climate change. The main reason for this is that water resources are not critical, but supply capacity and maintenance.

2.2.3 Climate change projections

The impacts of climate change on the hydrology of the ZRB have been extensively analysed in Sections 2.1.2 and 2.1.3. The findings indicate that rising temperatures and changing precipitation patterns will significantly alter the hydrological regime.

Projections show a substantial decline in glacier volume and snowmelt contributions, particularly under higher emission Shared Socioeconomic Pathway (SSP) scenarios. By the end of the 21st century, under SSP585, glacier volume is expected to decline by approximately 80%, while snowmelt runoff could decrease by up to 75% in certain months. This transition leads to a shift in peak river discharge from July to earlier months (June or even May) and an increasing contribution of rainfall-runoff. Consequently, total runoff is projected to decrease, which might exacerbate seasonal water shortages, particularly during the summer months when agricultural demand is highest.

To further understand the implications of these hydrological changes on water availability and allocation, Section 2.2.2 explored a set of sensitivity analysis within the WEAP modelling framework. These evaluations assessed the effects of altered supply and demand conditions, infrastructure constraints, and variations in management strategies. **The results underscored the importance of infrastructure improvements and adaptive management, demonstrating that even under current hydrological conditions, water shortages are driven more by accessibility issues than absolute water availability. Sensitivity analyses also highlighted the nonlinear responses of water allocation to changes in supply, emphasizing the need for robust, scenario-based planning.**

Building upon these sensitivity insights, a comprehensive climate change analysis was conducted using the WEAP model to assess the full range of projected climate scenarios as described in the previous chapters. A total of 15 distinct GCM-SSP model combinations were evaluated, based on the water resources analysis from SPHY. The full set of SPHY outputs were evaluated using WEAP on its impact on key water allocation metrics, including total demand, supply, and unmet demand (Figure 27).

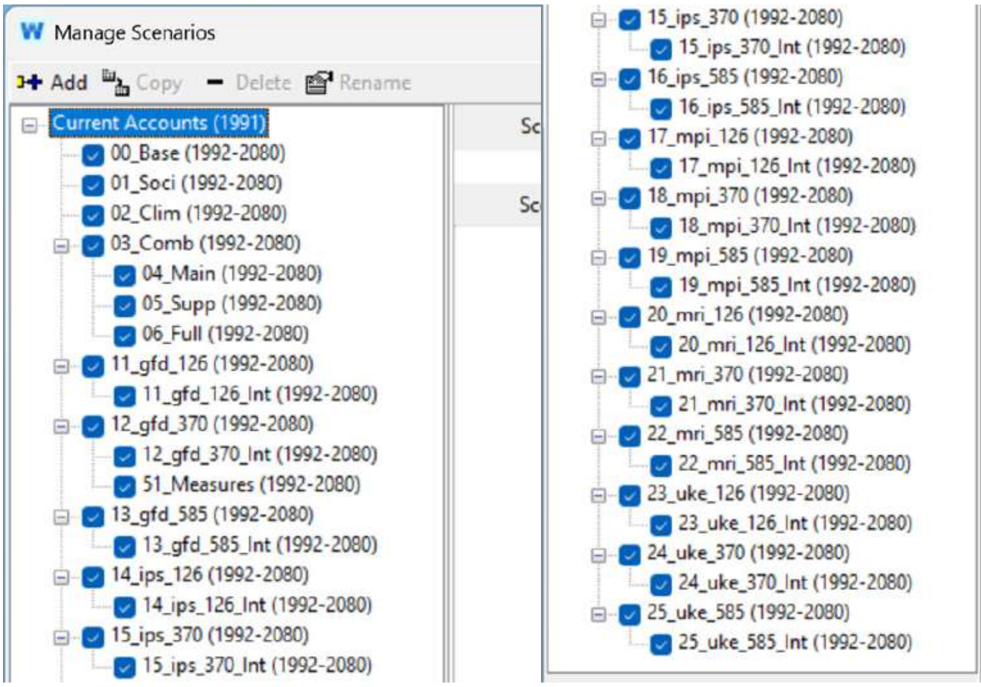


Figure 27. Screenshot of the scenarios (projections and interventions) as included in the WEAP model

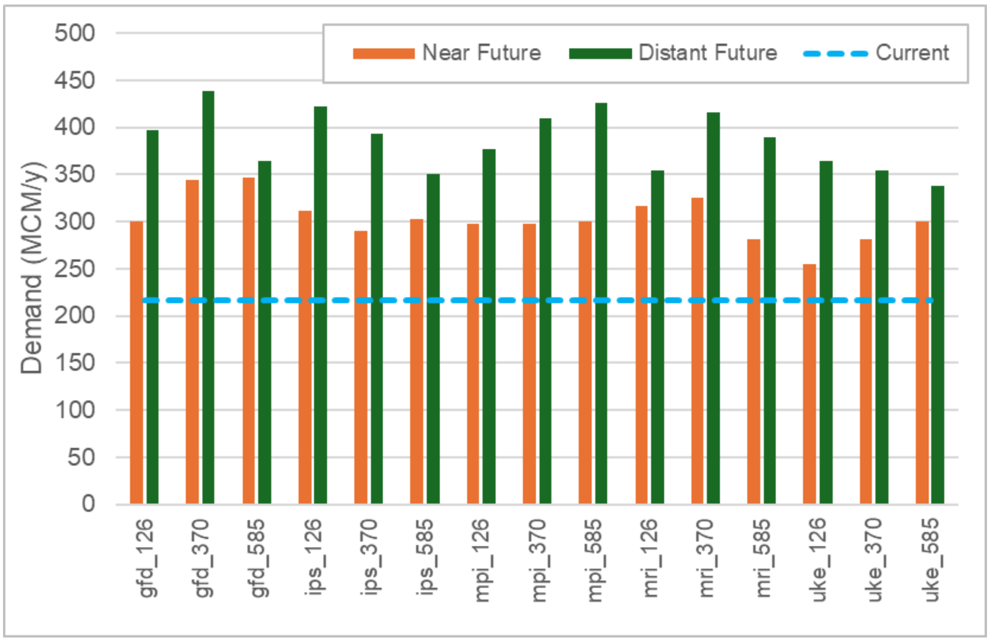
The full set of outputs from those analysis is substantial and can be obtained from the WEAP model itself. The most significant findings are shown in Table 13 and Figure 28, which reflect the same information in table and graph formats, respectively.

Figure 29 shows reduced streamflow levels at the outlet point of the ZRB before crossing into Uzbekistan, due to climate change.

Table 13. Water demand and unmet demand for the 15 GCM-SSP combinations. Near Future is 2031-2050; Distant Future is 2061-2080; Current reflects 2001-2020.

Water Components	Projections	Baseline and Time Horizons				
		Current (MCM/y)	Near Future (MCM/y)	Distant Future (MCM/y)	Near Future (% change)	Distant Future (% change)
Water Resources Availability	gfd_126	217	301	396	+39%	+83%
	gfd_370	217	344	439	+59%	**+102%**
	gfd_585	217	347	364	**+60%**	+68%
	ips_126	217	311	422	+44%	+95%
	ips_370	217	290	393	+34%	+82%
	ips_585	217	303	351	+40%	+62%
	mpi_126	217	298	377	+37%	+74%
	mpi_370	217	298	409	+37%	+89%

	mpi_585	217	301	426	+39%	+96%
	mri_126	217	317	354	+46%	+64%
	mri_370	217	325	416	+50%	+92%
	mri_585	217	282	390	+30%	+80%
	uke_126	217	255	364	**+18%**	+68%
	uke_370	217	282	354	+30%	+64%
	uke_585	217	301	338	+39%	**+56%**
Unmet demand	gfd_126	76	159	255	+109%	+235%
	gfd_370	76	202	297	+166%	**+291%**
	gfd_585	76	205	222	**+169%**	+192%
	ips_126	76	170	281	+123%	+269%
	ips_370	76	148	251	+95%	+231%
	ips_585	76	161	209	+112%	+175%
	mpi_126	76	156	235	+105%	+209%
	mpi_370	76	156	268	+105%	+252%
	mpi_585	76	159	284	+109%	+273%
	mri_126	76	175	212	+130%	+179%
	mri_370	76	183	274	+141%	+261%
	mri_585	76	140	248	+84%	+226%
	uke_126	76	113	222	**+49%**	+192%
	uke_370	76	140	212	+84%	+179%
	uke_585	76	159	196	+109%	**+158%**



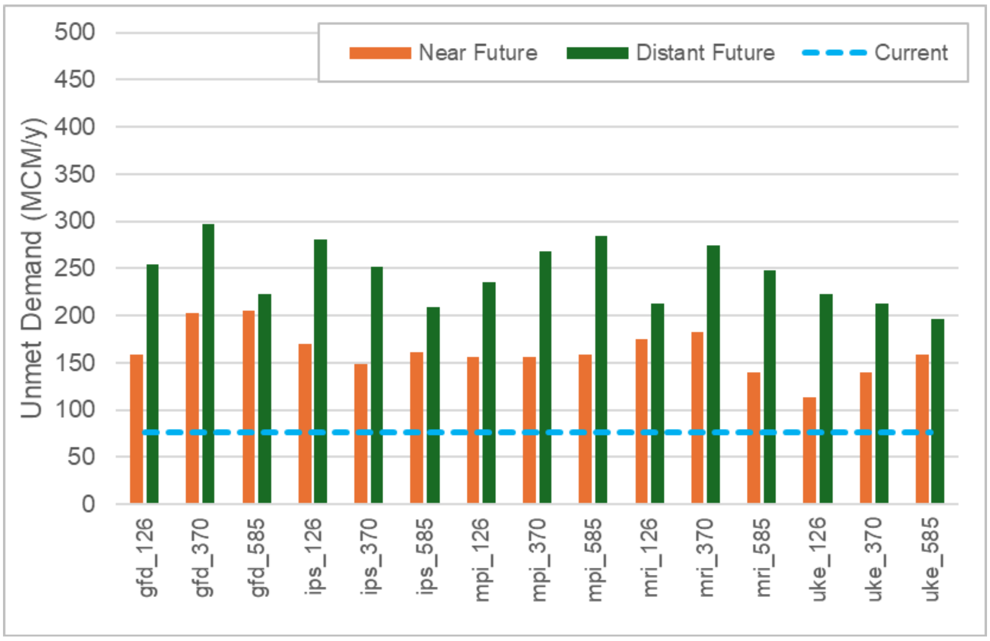


Figure 28. Average annual water demand (top) and unmet demand (bottom) for the 15 GCM-SSP combinations. Near Future is 2031-2050; Distant Future is 2061-2080; Current reflects 2001-2020.

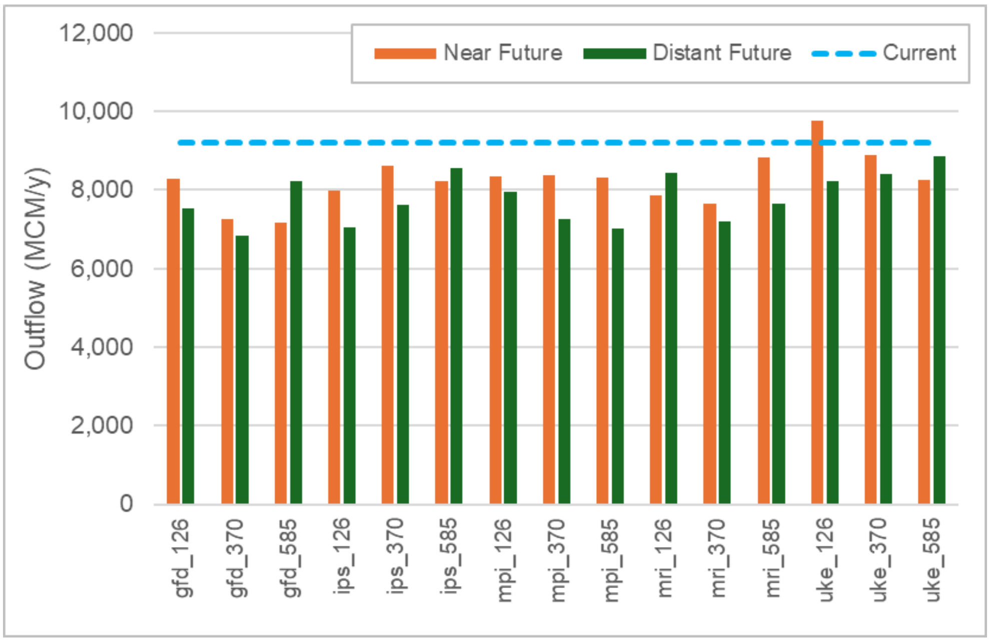


Figure 29. Average annual streamflow in MCM/y for 15 GCM-SSP combinations at the outlet point of the Zarafshon. Near Future is 2031-2050; Distant Future is 2061-2080; Current reflects 2001-2020.

The **most important conclusions** from the Tables and Figures above, regarding the impact of the full range of projected climate scenarios on water demand and water allocation can be summarized as follows:

Water demand is expected to increase by 18% to 60% in the near future, and 56% to 102% in the distant future. This increase in water demand occurs as less rainfall will occur and higher temperatures can be expected.

The water shortage (unmet demand) will increase even further with average values of 113% for the near future, and 222% in the distant future. Detailed analysis shows that this water shortage is **mainly due to lack of water accessibility (water infrastructure).** This is clearly demonstrated by the **streamflow at the outlet point of the Zarafshon river basin, which is reduced due to climate change,** but still some orders of magnitude higher than the unmet demand.

2.2.4 Climate change interventions

In Section 2.2.2, a range of interventions was introduced to evaluate their effectiveness in mitigating water shortages. These interventions concentrated on increased conveyance infrastructure capacity (maintenance upgrade and supply expansion). The analysis demonstrated that investments in the supply infrastructure could significantly reduce unmet demand and improve overall water security in the Zarafshon river basin.

Building upon these insights, the same interventions were systematically evaluated across the full range of 15 climate scenarios using the WEAP model.

The full set of outputs from those analysis is substantial and can be obtained from the WEAP model itself. The main results are presented in Table 14 and

Figure 30, which reflect the same information in table and graph formats, respectively. Figure 30 (second graph) shows additionally a minimal impact of those interventions on the overall water resources availability in the Zarafshon river basin.

Table 14. Unmet demand for the 15 GCM-SSP combinations. Table presents the impact of climate change (Projections) and to what extents Interventions might reduce this unmet demand. Near Future is 2031-2050; Distant Future is 2061-2080.

GCM-SSP model combinations	Reduction in Unmet Demand under different Time Horizons					
	Near Future			Distant Future		
	Projected Unmet Demand[8] (MCM/y)	Interventions[9] (MCM/y)	Reduction (%)	Projected Unmet Demand[10] (MCM/y)	Interventions (MCM/y)	Reduction (%)
gfd_126	159	56	-65%	255	143	-44%
gfd_370	202	93	**-54%**	297	184	**-38%**
gfd_585	205	96	-53%	222	112	-50%
ips_126	170	65	-62%	281	168	-40%
ips_370	148	48	-67%	251	140	-44%
ips_585	161	58	-64%	209	100	-52%
mpi_126	156	54	-65%	235	124	-47%
mpi_370	156	54	-65%	268	156	-42%
mpi_585	159	56	-65%	284	172	-40%
mri_126	175	69	-61%	212	103	-52%
mri_370	183	76	-59%	274	162	-41%
mri_585	140	43	-70%	248	137	-45%
uke_126	113	26	**-77%**	222	112	-50%
uke_370	140	43	-70%	212	103	-52%
uke_585	159	56	-65%	196	88	**-55%**

8 See Table 13, where it is shown how unmet demand is expected to increase by 113% on average for the near future.

9 Interventions are focused on increasing the conveyance capacity of water infrastructure through adequate maintenance upgrade and supply expansion.

10 See Table 13, where it is shown how unmet demand is expected to increase by 222% on average for the distant future.

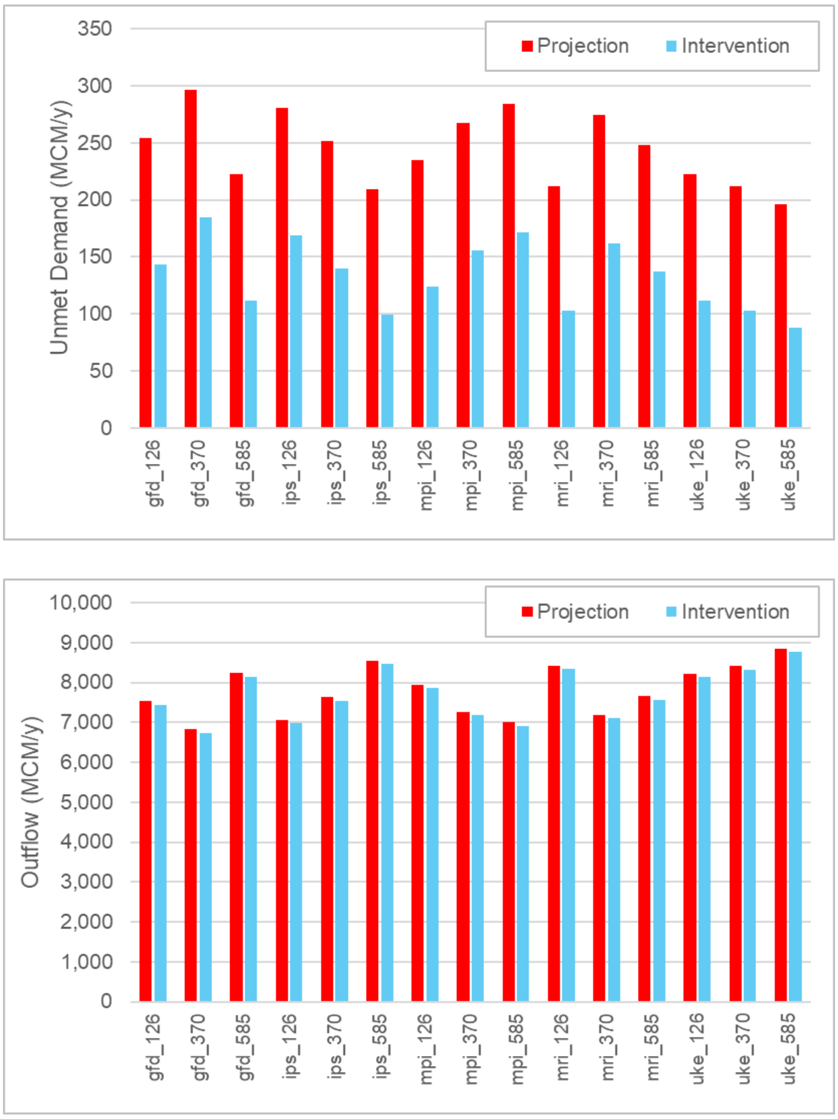


Figure 30. Impact of interventions (enhanced infrastructure) on reducing unmet demand (top) and on streamflow at the outlet point of the Zarafshon. Results are reflecting the distant future (2061-2080). Note the difference in Y-axis ranges.

The **most important conclusions** from the Tables and Figures above, regarding how projected unmet demand increases can be reduced through interventions focused on increasing the conveyance capacity of water infrastructure through adequate maintenance upgrade and supply expansion, are as follows:

The interventions can effectively reduce water shortages. For the near future average water shortages (along all GCM-SSP) can be reduced from 162 to 60 MCM/y (64%). For the distant future a reduction from 224 to 134 MCM/y (46%) can be achieved. The impact of those interventions on water resources is quite limited. Overall streamflow, as defined at the outlet point of the Zarafshon river basin, is around 1%. It is clear that water resources are not critical under none of the climate scenarios, but that supply capacity and maintenance of water infrastructure are still limiting water supply.

2.3 Linkages with IRDP/TRIGGER

2.3.1 Relevance

The “Integrated Rural Development Project” (IRDP) aims “to boost added value of agricultural production”. GIZ implements the activities of IRDP as part of the bilateral development project “Towards Rural Inclusive Growth and Economic Resilience (TRIGGER)” in Tajikistan and is funded by BMZ. The aim of the Integrated Rural Development Project (IRDP/TRIGGER) is the following: The economic resilience of micro, small and medium-sized enterprises including smallholder producers is strengthened.

The Water Output of the IRDP/TRIGGER initiatives provides technical support to the MEWR at national and river basin levels to advance the Water Sector Reform Process. At the local level, the Water Output operates in ZRB. It aims to improve the enabling environment in the water sector in Tajikistan and advance the implementation of relevant water-related national policy in regional and local development processes.

The Water Output seeks to integrate and safeguard climate change adaptation in local and regional plans that are relevant to small-scale farmers. This integration is planned through the formulation, implementation, monitoring and evaluation of climate-sensitive river basin management plans, that incorporate an integrated water resources management approach, and their eventual mainstreaming into small-scale farmer relevant development plans.

The Project supports the adaptation of agriculture to climate change for irrigation measures to be planned in a way that the water resource can be sufficiently and effectively accessed and used more sparingly by farmers. The lessons learned from experiences implemented at the local and river basin levels must feed into the national water-related policy and inform the Water Sector Reform Program.

2.3.2 Measures (interventions)

Within the process of formulation of the ZRBMP, the Zarafshon RBO and River Basin Council, with the support of the IRDP/TRIGGER project, have identified over 100 potential interventions (called “measures” in the IRDP/TRIGGER project). Those potential measures range from very small-scale demonstration irrigation plots (< 1 ha) to a complete rehabilitation program of the Khalifa Hassan canal.

The measures include irrigation as well as drinking water supply. A total of 114 measures have been identified and the total impact on water resources will be about 290 MCM/y.

Table 15 and Figures 31, 32 and 33 below reflect the main statistics and figures summarizing the proposed measures.

Table 15. Overview of measures as defined during IRDP/TRIGGER project.

River	Number of Measures		Total Supply (MCM/y)	
	Irrigation	Domestic	Irrigation	Domestic
Farob river	3	0	2.7	0.0
Fondarya river	12	7	4.9	0.4
Kishtut river	5	1	22.3	0.1
Magiyan river	23	10	71.0	18.9
Matcha river	33	10	113.0	0.5
Zarafshon downstream river	4	0	45.6	0.0
Zarafshon upstream river	4	2	7.7	1.9
TOTAL	**84**	**30**	**267.3**	**21.8**

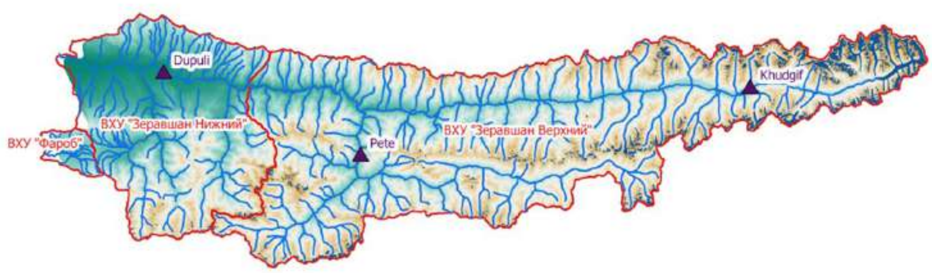


Figure 31. Water management areas as used to aggregate the proposed measures. In total 2 "water management areas" are defined in the Zarafshon River Basin.

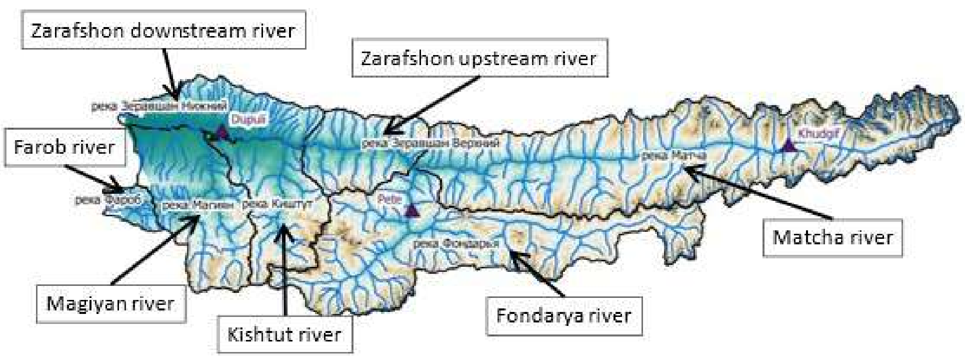


Figure 32. Water body areas as used to aggregate the proposed measures. In total 7 "water bodies" are defined in the Zarafshon River Basin.

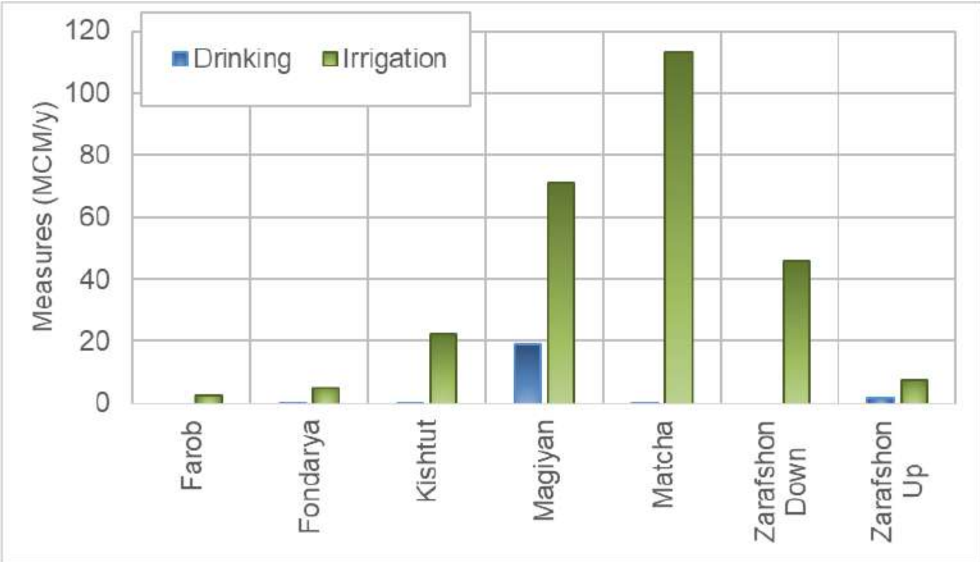


Figure 33. Sum of volume of water use and additional water consumption in million m3/season (MCM). The Figure shows the total for all the proposed measures in the ZRB aggregated at the river level ("Water Body").

2.3.3 Impact on water resources

The impact of all the proposed measures was analysed using the results of the WEAP model as presented in the previous sections. In Figure 34, **the analysis shows clearly that the water demand in the proposed measures discussed by the Zarafshon RBO and Council with the support of the IRDP/TRIGGER project are substantial compared to the current water demand in Zarafshon river basin.** Especially for the Magiyan and Matcha water demand is currently high and will be more than double when all measures are implemented. Also, for the other rivers ("water bodies") the increase in water demand will be substantial.

Many of the proposed measures are not new developments but are rehabilitations of outdated water supply infrastructure. It is therefore interesting to explore the relationship between those proposed measures and the current unmet demand (water shortage). As reported earlier, the current shortages are not induced by water resources availability but by insufficient water supply infrastructure. As shown in Figure 35, **for all the "water bodies" the proposed measures are higher than the unmet demand, with the exception of Farob River. So, one can conclude that the proposed measures are all well planned.**

Finally, the question is whether there is sufficient water available to implement those measures. Figure 36 shows again the water demand within the seven "water bodies" and water availability based on the WEAP model analysis. It is clear **that water resources are abundant to provide water for all the proposed measures. Even if the dryest year over the last 20 years is considered, no restrictions in water resources will occur in the Zarafshon River Basin.**

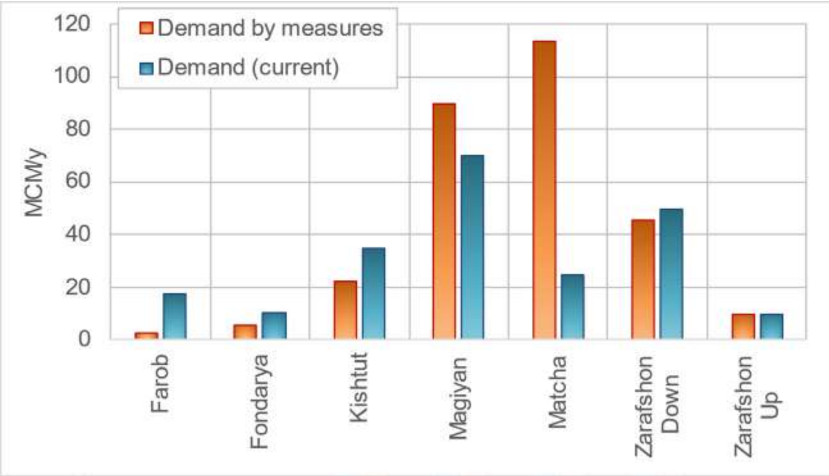


Figure 34. Comparing current demand (all sectors: irrigation, domestic, livestock, industry) with additional demand by the proposed measures. The Figure shows the total aggregated at the river level ("Water Body").

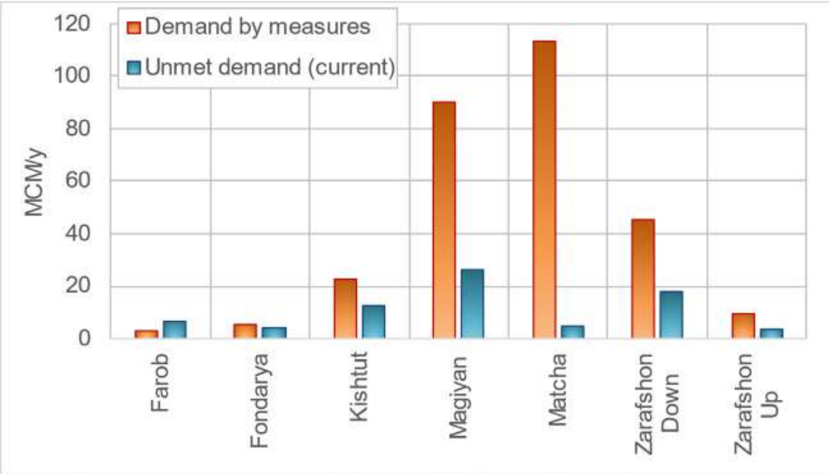


Figure 35. Comparing current unmet demand (water shortage) with additional demand by the proposed measures. The Figure shows the total aggregated at the river level ("Water Body").

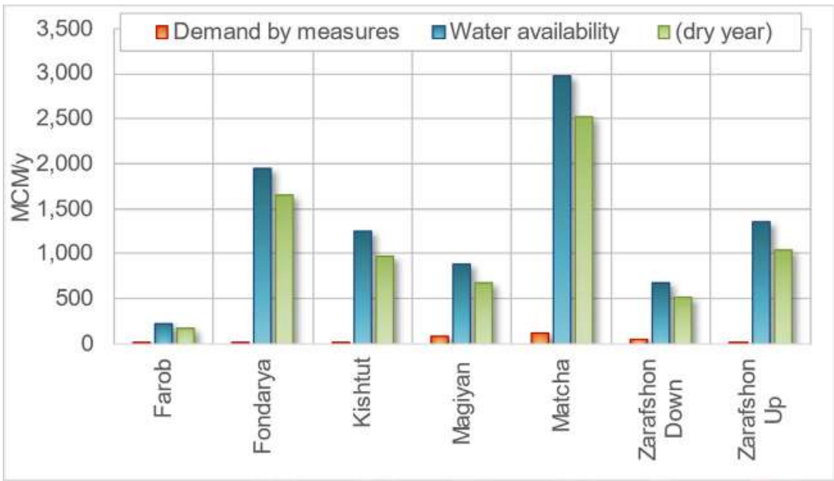


Figure 36. Comparing current water availability (for an average and a dry year) with additional demand by the proposed measures. The Figure shows the total aggregated at the river level ("Water Body"). Note that numbers of "demand by measures" are exactly same as in. Note: y-axis is different compared to the previous two Figures.

2.3.4 Measures evaluated in WEAP

The IRDP/TRIGGER project aims to enhance water management and agricultural resilience by implementing a series of 114 measures across the Zarafshon River Basin. These interventions, as described in Section 2.3.2, primarily focus on irrigation infrastructure rehabilitation and drinking water supply improvements, ensuring better water distribution and accessibility. The total estimated impact of these measures on water resources is approximately 290 million cubic meters per year (MCM/y).

An assessment of the impact of these measures, as outlined in Section 2.3.3, highlighted their significant contribution to addressing current water shortages. Many of the measures involve the rehabilitation of outdated water supply systems, rather than new developments. **The analysis showed that in most cases, the additional demand generated by these measures exceeds the current unmet demand, indicating that water availability is not the primary constraint—rather, infrastructure limitations are the key challenge. Importantly, even in the driest recorded years, the total available water in the ZRB remains sufficient to meet demand, provided that infrastructure improvements are made.**

Given the uncertainties related to future climate conditions, it was necessary to evaluate the effectiveness of these proposed measures under climate change using the WEAP model. To assess their impact under the most water-limiting scenario, the measures were tested using the gfdl_370 climate projection, which represents one of the driest and most extreme cases for the region. The WEAP analysis allows for a realistic assessment of intervention feasibility under adverse future conditions, ensuring that the proposed measures remain effective in mitigating water scarcity risks.

An overview of the results is summarized below in Table 16, Figure 37 and Figure 38, which show the same information in table and graph formats, respectively. Figure 38 (third graph) shows additionally a minimal impact of those interventions on the overall water resources availability in the ZRB at the outlet before crossing the border into Uzbekistan, as compared to climate change.

Table 16. Overview of the impact of the "Measures" as proposed by the Zarafshon RBO and Council with the support of the IRDP/ TRIGGER project as analyzed by the WEAP model. Based on the current situation (no climate, no interventions); gfd_370 is the climate projection; +measures are the Measures as defined by the Zarafshon RBO and River Basin Council. Results are for the distant future (2061-2080) as averages per year.

(MCM/y)	Base	gfd_370	+measures
Farob river	217	439	1,054
Fondarya river	141	142	633
Kishtut river	76	297	422
Outflow	9,219	6,823	6,436

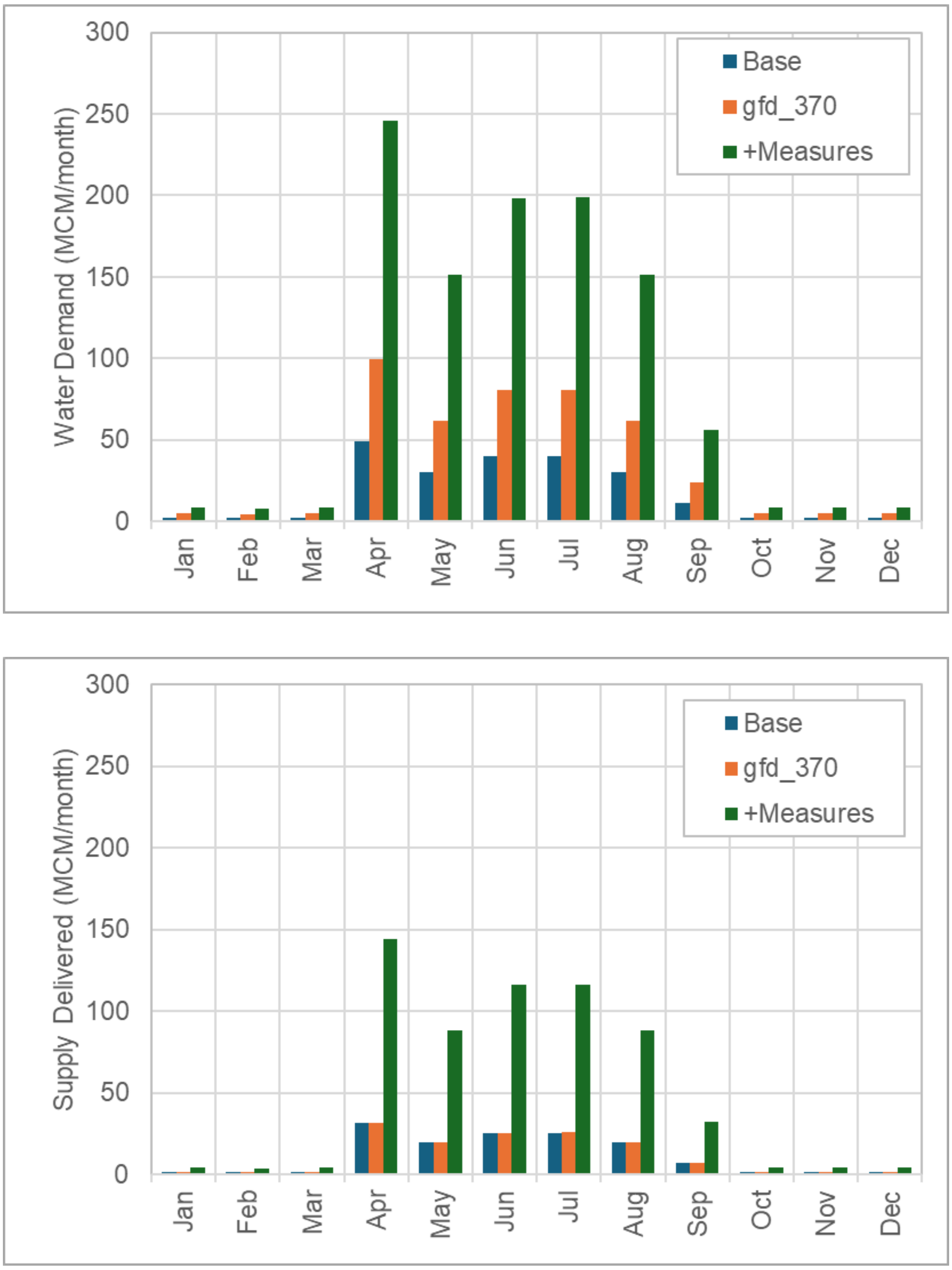


Figure 37. Average monthly water demand (top) and supply delivered (bottom) for the distant future (2061-2080) as evaluated using the WEAP model. Base is the current situation (no climate, no interventions); gfd_370 is the climate projection; +measures is the Measures as defined by the Zarafshon RBO and Council with the support of the IRDP/TRIGGER project.

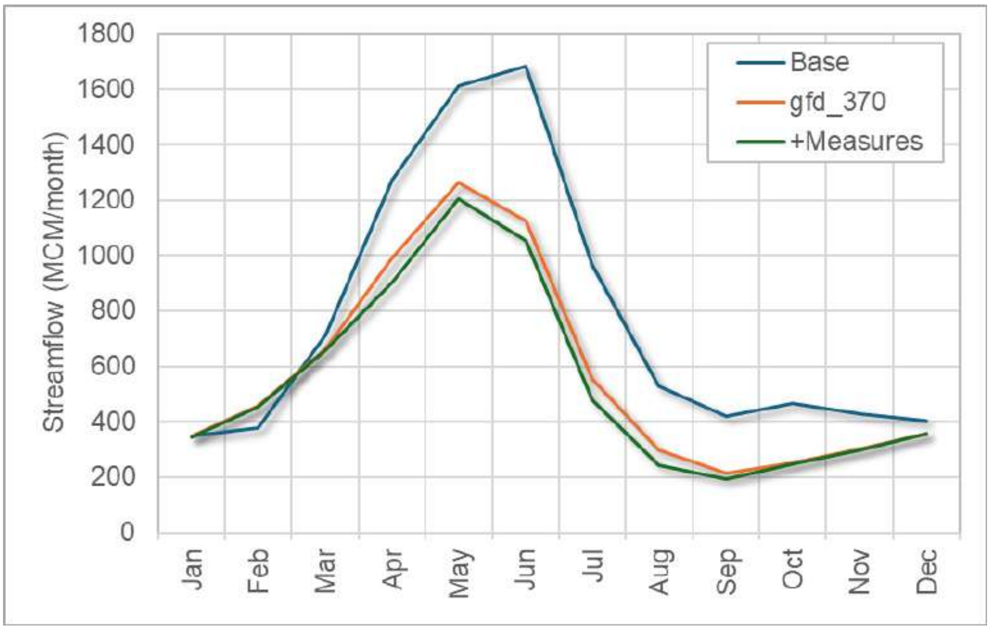


Figure 38. Impact of the Measures on streamflow at the outlet point of the ZRB for the distant future (2061-2080) as evaluated using the WEAP model. Base is the current situation (no climate, no interventions); gfd_370 is the climate projection; +measures is the Measures as defined by the Zarafshon RBO and Council with the support of the IRDP/TRIGGER project.

Detailed results can be found in the WEAP model; however, the main findings show the following:

The proposed measures will have a substantial impact on total water requirements. Considering the most drastic climate change projection (gfdl_370), water demand will be more than double. Supply will increase substantially under those measures, but still not sufficient to fulfil the complete water demand. Additional infrastructure development (maintenance and capacity) is still needed. Water resources, defined as the streamflow at the outlet point of the ZRB before crossing the border into Uzbekistan, are affected. However, the impact of climate change is much bigger compared to the impact of the proposed measures.

3. RECOMMENDATIONS

3.1 Addressing Limitations and Gaps

3.1.1 Hydro-meteorological data

The results of this study are largely based on the ERA5 reanalysis data downscaled using TopoSCALE and are therefore subject to the limitations inherent in these data. The primary purpose of the downscaling scheme is to correct the bias between large-scale reanalysis data and the fine-scale model grid, such as the difference in air temperature due to elevation variations. However, initial biases in the reanalysis data persist, particularly due to the density of observations assimilated and their availability to correct the model. In general, mountainous regions in Tajikistan and Central Asia are relatively data-poor, which results in non-convergent reanalysis data products for these areas. **The lack of hydro-meteorological data hinders the calibration and validation of the hydrological model, thereby compromising its quality and credibility.**

Sufficient effort must be targeted to enhance the hydro-meteorological network and long-term data monitoring. To cater for this, new meteorological stations were installed in the ZRB (see Annex 3: Meteorological stations installation in the ZRB in Tajikistan). The local stakeholders are recommended to integrate the data collected from these meteorological stations into the SPHY model and recalibrate and validate the model parameters with new data. Stakeholders must ensure that sufficient efforts should be targeted to enhance the long-term monitoring of the bio-physical variables.

3.1.2 Snow Data

Snowmelt runoff is a major contributor (~53%) to the flow of the ZRB, making it essential to calibrate and validate the snowmelt-related processes (snow water equivalent, snow depth, snow cover etc) in the model. Despite significant efforts to acquire local-scale observed data, a substantial portion, particularly snow and glacier-related data, could not be obtained, either because of the lack of instrument to collect the relevant data or because of reluctance to share available datasets at local level by different relevant stakeholders. Consequently, available open-source data, including satellite data, were used for the modelling work. Information from literature and freely accessible public domain data were also incorporated, with data from various open-source platforms combined to model and validate the results of this project.

To improve the understanding of snowmelt-related processes, two drone[11] data collection expeditions together will all the relevant national stakeholders were conducted at the GGP glacier during the course of the project (Table 1). Drone technology is well-suited for analysing seasonal snow variability in harsh climates and complex topography due to its ability to capture high-resolution data, navigate rugged and remote areas, and conduct frequent, cost-effective surveys. They provide detailed insights into snow distribution, depth

11 Building on the capacity building improvements achieved by the local stakeholders with the support of the IRDP/TRIGGER Project and its Consortia partners, a third glacier expedition to the GGP glacier was carried out in May 2025 to collect relevant snow and glacier-related data using drone technology. The third glacier expedition was also supported by IRDP/TRIGGER Project.

patterns, and properties with the use of multispectral cameras, which are difficult to obtain through traditional ground-based methods. Additionally, drones enhance safety by eliminating the need for human presence in hazardous environments and enable real-time data processing for timely decision-making. Their flexibility, precision, and efficiency make them an invaluable tool for studying dynamic snow cover changes in challenging terrains.

These expeditions aimed to capture detailed spatial and temporal data on snow and ice dynamics, which could help refine the modelling of snowmelt runoff. However, results from the drone expeditions were not fully incorporated into the modelling exercise due to time constraints and logistical challenges. These included the loss of the fixed-wing eBee X drone during the first expedition and customs restrictions preventing the use of the DJI Mavic 3 copter at the glacier during the second expedition. The drone data collection should be complemented by the traditional in-situ data collection to improve the accuracy of the data collected via drone.

Given the importance of snow in ZRB and in Tajikistan, it is recommended that stakeholders having mandate to collect data in high-mountains regions continue these drone-based data collection efforts in the coming years. Establishing a long-term series of high-resolution data will provide a more comprehensive dataset for incorporation into future hydrological models, enhancing their accuracy and robustness.

3.1.3 Glacier data

Glaciological measurements in high mountains pose unique challenges due to their inaccessible terrain, harsh weather conditions, limited data transmission and power supply and complex environmental factors. **Establishing and maintaining measurement stations in such remote locations can be difficult, and extreme weather can damage instruments and hinder data collection.**

The calibration of glacier processes was carried out using the altitudinal Surface Mass Balance (SMB) data from four major glaciers in the ZRB basin: Zarafshon, Rama, Rossnich, and Shakhisafid glaciers. **These four glaciers were selected as representative of the entire ZRB.** Observed glacier mass balance, ice thickness, and glacier outlines across the entire Zarafshon River Basin, which were necessary to calibrate and validate the glacier processes in the model, were not available for this project. Only the topography and outlines for the GGP glacier were collected during the first glacier expedition. Hence, the glacier outlines and thicknesses used in the model were obtained from publicly available datasets (Annex 2: Explanation of the model, data and methodologies). **A good timeseries for GGP glacier and other relevant glaciers in ZRB could prove useful to calibrate and validate the glacier processes in the SPHY and WEAP model chain.**

However, the data obtained from regional and global estimates carry inherent uncertainties, which can propagate into the hydrological simulations. To address this, two drone-based data collection expeditions, in conjunction with traditional glacier data collection methods, were organized during the project duration to gather more localized and high-resolution data. It is recommended that stakeholders continue these data collection efforts in the future to deepen the understanding of glacier changes.

Long-term monitoring of glacier dynamics is crucial for refining glacier processes in hydrological models and enhancing the accuracy of predictions related to water flow and availability in the region. Therefore, **stakeholders should focus their efforts on ensuring sustained monitoring of benchmark glaciers, rather than dispersing resources across multiple glaciers.**

3.1.4 Water supply and demand data

Water supply and demand data are collected in considerable detail by various water management authorities. Significant ongoing efforts aim to better organize, standardize, and improve the accessibility of these data. For the water demand and shortage analyses presented in this report, which were conducted using the WEAP model, these datasets were utilized extensively.

One of the key intervention scenarios explored in this report involves **enhancing maintenance levels and expanding supply capacity.** However, these aspects **are notably characterized by significant data gaps and uncertainties. Addressing these gaps and subsequently improving maintenance (Box 10) and supply service levels requires a more systematic and rigorous approach.**

This would involve not only enhanced monitoring and reporting of infrastructure performance, including failures in supply services and operational issues in smaller infrastructure elements such as canals, pipelines, and pumps, but also more comprehensive data collection strategies. While such monitoring efforts can be time-intensive and resource-demanding, alternative or supplementary methods, such as structured interviews and surveys targeting water consumers, could provide valuable insights. These approaches could help identify critical areas for improvement and support evidence-based interventions in water resource management.

3.2 Upscaling of the modelling approach

Upscaling of the modelling approach refers to the process of extending or adapting existing SPHY and WEAP model suits to different river basin zones in Tajikistan, including larger spatial and/or temporal scales. Scaling up of these model suits can be necessary to address various challenges, such as studying national or regional water resources management, understanding the impacts of climate change on hydrological processes, or supporting decision-making for water-related infrastructure projects. **Scaling up of the models can be challenging due to the complexities and uncertainties associated with hydrological processes at larger scales, the availability and quality of data, and the computational requirements of larger models.**

3.2.1 SPHY

SPHY was developed with the explicit aim to simulate the mountain hydrological processes at flexible scales, under various land use and climate conditions. **Since the input data required to set up the SPHY model as described in** 'Annex 2: Explanation of the model, data and methodologies' **is mostly available for the entire HMA region, the SPHY model can be easily scaled-up or applied to the different regions of Tajikistan and Central Asia.**

The basins adjacent to each other with similar climatic and physiographic characteristics tend to hydrologically behave in a similar manner (Merz and Blöschl, 2004; Patil and Stieglitz, 2014). Thus, the calibrated parameters (see A2.1.6 Model Calibration) can be transferred to a hydrologically similar basin in Tajikistan and Central Asia. A "vector teams" approach, where the replica of the parameters from the gauged catchment can be transferred to the ungauged catchment, could be used for basins in the Central Asia and HMA region (Bárdossy, 2007). This approach has been widely used for regional SPHY studies where there is a lack of available discharge data (Khanal et al., 2021; Lutz et al., 2014; Wijngaard et al., 2017). **However, proper validation and verification of scaled-up and replicated models are essential to ensure their reliability and accuracy. If data is available, the key processes such as glaciers, snow, and rainfall-runoff should be validated.**

Region-wide observed glacier mass balance information is not available in most cases. However, for specific glaciers, some information is available in the public domain (i.e., published scientific articles, reports, and websites). **SPHY is flexible enough to incorporate the data at both individual glacier and large basin level aggregation.** For instance, if there is information available on glacier mass balance for multiple glaciers in a basin then different glacier mass balances could be used to parameterize the glaciers. However, if such information is not available then only one glacier-mass-balance for the whole basin can be used to parameterize the glacier processes.

Either limited or no discharge data availability for the hydrological model calibration is a key issue in the data scarce Central Asian region. In such basins, where the discharge measurements are available, a validation of the simulated flux (i.e., simulated discharge) is essential. The replicated parameters could be re-adjusted based on the discrepancy between the simulated and the observed discharge as explained in the model calibration sub-section of Annex 2: Explanation of the model, data and methodologies.

If the observed discharge data is not available then secondary sources of information from the journal, articles, and reports should be used to validate the model. For instance, i**f the daily time series of observed discharge is not available, the model can still be calibrated based on the monthly/annual average values available from secondary sources. Satellite information can be highly valuable in calibrating hydrological models due to its ability to provide data on various hydrological parameters at large spatial and temporal scales.** For instance, satellite-derived soil moisture data and river discharge data, such as those from radar altimetry or optical sensors, could be used to calibrate river discharge in hydrological models, helping to validate model outputs and improve their accuracy. However, it's important to carefully assess the quality and limitations of satellite data, as well as consider the uncertainties associated with hydrological processes, when using satellite information for model calibration and validation.

3.2.2 WEAP

The WEAP model developed for the ZRB can be used as a base for further upscaling to other basins or regions in the country. Setting up the model for other basins is not complex, as the main approach used here can be easily adopted. A point of attention is the level of detail to be included. In other words, in the current approach, aggregated Jamoats were used as the analysis unit. In other regions, one might consider different aggregation levels or approaches. This depends on the objective of the model and also on the availability of data and the aggregation level at which this data is collected.

Another aspect of upscaling of the WEAP model to other regions is focus right from the beginning on what kind of scenarios (projections and interventions) should be evaluated. This is of high relevance as it determines the model setup and data requirements.

At an operational and managerial level, it is crucial to consider where, and by whom, the model will be developed when upscaling to other basins, as well as identifying the intended end-users once the model is finalized. This consideration includes updating protocols to ensure the model is tailored to its purpose—whether it will be primarily used for **strategic, tactical, or operational objectives.** Defining these aspects during the development phase will help align the model's structure, functionality, and data requirements with the specific needs of the stakeholders and ensure its effective implementation and usability across different regions.

3.3 Enabling environment to upscale the approach

Accelerated warming is expected to disrupt the hydrological cycle as we know it in ZRB and in other river basin zones in Tajikistan and Central Asia, particularly, the mountain hydrology and ecosystems, impacting biodiversity and water resources. Strong adaptation measures are essential to mitigate these effects and protect mountain communities.

Equally important is the need to complement infrastructure projects with soft interventions, such as capacity-building, knowledge sharing, and community engagement, to ensure a comprehensive approach to climate resilience. Based on the project's experience, the following recommendations are proposed to the national stakeholders, bilateral donor agencies, financial institutions and MDBs to build resilience against the changing climate in ZRB and Tajikistan.

3.3.1 Open, digital and central database for effective information systems

Currently, national stakeholders (THA, CGR, IWP, TAU) collect in-situ data independently, store the data in analogue format and requiring digitalization. This approach limits interdisciplinary research, policy development, and collaboration, and is prone to data collection overlaps or just make it difficult to target existing data gaps.

Implementing robust centralised data management systems within NWIS and promoting open data sharing will improve access to climate and water information. **Standardized tools across relevant stakeholders for data collection and analyses will foster collaboration, streamline research, and enable deeper analyses, strengthening scientific inquiry.** Better data availability will support evidence-based decision-making for more effective climate and water solutions.

3.3.2 Long term data monitoring and focused multisectoral technology investments

Targeted and strategic investment in technology is essential to significantly improve the frequency, accuracy, and geographical coverage of cryosphere and hydro-meteorological monitoring. Various sensors, technologies and proven methods can be employed to collect hydro-meteorological data, capturing key information about the cryosphere, meteorological variables and water cycle. The selection of sensors is determined by the specific research or monitoring goals, the variables of interest, and the environmental conditions of the study area. **Long-term monitoring will enable a more comprehensive and timely understanding of the key hydrological processes that are critical for assessing and managing water resources in the ZRB and Tajikistan.**

By enhancing the quality and scope of monitoring efforts, stakeholders can gain more reliable insights into the complex interactions within the cryosphere, which directly affect sustainable economic development, particularly in sectors heavily reliant on water availability, such as agriculture, energy, and infrastructure.

Thanks to the support of the IRDP/TRIGGER Project, the MEWR and other relevant stakeholders realized the **high amount of time and financial resources that are needed to ensure that a limited and selected number of staff across different relevant institutions can actually achieve higher levels of modelling capacities enough to carry on the efforts beyond the lifespan of the IRDP/TRIGGER Project. It is an effort that goes beyond any given project.** In this sense, local and international development partners should direct and focus their efforts on building capacity of targeted staff on specific hydrological modelling and cryosphere monitoring technology that has proven to be effective, even if this means following up previous efforts from former projects funded by different development partners and supporting the same technology.

3.3.3 Mastering a single but proven model and technology

To maximize the impact of investments, **it is crucial to prioritize proven models and technologies with a demonstrated track record of success.** Spreading resources across multiple, untested options could lead to inefficiencies and dilute the effectiveness of monitoring efforts. Instead, the focus should be on technologies that have already proven their reliability and scalability, ensuring that investments are both cost-effective and impactful.

Furthermore, **local stakeholders (THA, CGR, IWP, TAU) should focus their efforts on mastering a single, effective model or technology.** This approach will enable them to develop deep expertise and achieve more meaningful, long-term results, rather than spreading their efforts too thin by attempting to learn and implement several models at a superficial level.

The SPHY and WEAP models have proven to be highly versatile and effective in ZRB, delivering reliable and near-accurate simulations of cryospheric and hydrological processes. As free, open-source tools, they enable seamless integration of ground-based and satellite-based data, offering a scalable and adaptable solution for extending their use to other river basins in Tajikistan and Central Asia.

By concentrating on one well-established approach, local teams can build the capacity needed to drive continuous improvements in monitoring and modelling, thereby contributing to more accurate and actionable data that can support sustainable water management and economic development in the region.

3.3.4 Capacity-building to improve the skillsets of the local water professionals

Enhancing national technical capacity to assess and monitor changes in cryospheric and hydrological systems through innovative modelling tools and techniques will enable stakeholders to effectively manage sustainable water allocation and use.

To equip stakeholders with the necessary knowledge and skills (drones, data collection, modelling, analysis, data-information-translation, etc), over 150 hours of intensive technical training are required. To ensure scalability and sustainability, this project has adopted a **«training-of-the-trainer» approach.** Several **'young champions'** have been identified from among the stakeholders, who can assist the departments in further enhancing the skill sets of other water professionals across the country.

It is recommended that national stakeholders continue capacity-building efforts beyond the project's duration and incorporate training components into future project designs.

3.3.5 Integrated water resources management is an iterative process that requires reforms at regular interval that should be reflected and updated into the model

The IWRM approach is an ongoing process that requires regular updates and reforms. As socio-economic development priorities, policies, and plans evolve each year, therefore **national stakeholders are recommended to communicate effectively and adjust their priorities and scenarios in the model.**

Mastery in these areas requires more than a single project's duration, necessitating ongoing investment in skilled water professionals with advanced mastery on tools and technologies.

Additionally, ensuring equal youth and gender representation and prioritizing inclusive planning will contribute to the creation of comprehensive, strategic management plans that address diverse needs and perspectives.

3.3.6 Adaptation in mountains is difficult and it requires interagency co-operation

Mountain adaptation requires an interagency cooperation framework across technology investments, capacity-building efforts, and data information systems.

Effective climate information services, which provide critical climate-related information across multiple sectors such as water management, are essential in addressing the rising frequency of water-related hazards like floods and droughts caused by climate change. These services rely on collaboration with various stakeholders—governments, communities, and local water managers—to ensure that the information is both relevant and inclusive. By involving stakeholders in monitoring and decision-making, transparency is increased, and collaboration is strengthened, ultimately improving the effectiveness of these services. It is also essential to communicate findings and decisions clearly to affected communities and economic sectors, as increasing climate awareness in Tajikistan is key to understanding and adapting to their unique environmental challenges.

In this sense, the Zarafshon RBO and River Basin Council provided the right institutional framework to communicate the findings of this work as well as obtain relevant data that was then introduced into the SPHY and WEAP model.

3.3.7 International cooperation and partnership

National stakeholders, including ministries, research institutes and non-governmental organizations, are encouraged to collaborate with regional and international partners to bring new technology and investments into Tajikistan.

It is recommended that national stakeholders take proactive steps to foster and cultivate a collaborative environment in Tajikistan, where international experts and institutions can work together effectively. This should involve creating opportunities for knowledge exchange, efficient tool and technology transfer (including custom clearance administrative processes and channels), joint initiatives, and open dialogue, ensuring that global expertise is leveraged to address local challenges and enhance the country's development efforts.

Open data and research could be one of the key enablers for the experts and research institutes. Additionally, national stakeholders should leverage existing knowledge from the regional and global community of scientific experts, institutions and innovators.

ANNEX 1: KEY FEATURES OF THE STUDY AREA

A1.1 Overview

The Zarafshon river, a tributary of the transboundary Amu Darya River, originates at the Zarafshon glacier, at an altitude of 2775 m, at the junction of the Turkestan and Zarafshon ranges, both of them belonging to the western sector of the Pamir-Alay system (Figure 39). The initial part of the river, about 300 km long, lies in a narrow, deep valley. On the southern left bank, flowing between the Turkestan and Zarafshon ranges, it receives the Yagnob, Arthuch and Mogiyon rivers, as well as many small tributaries[12]

Zarafshon translating to «gold-bearing,» the name of the river reflects its historical association with gold. While extractable gold in the main riverbed is limited, the river's tributaries and surrounding geological formations boast significant gold deposits. This region hosts the largest gold mining enterprises in Tajikistan and Uzbekistan.

ZRB with an area of 17,700 km^2 (only Tajikistan part), covers diverse geological formations spread from the alpine zone, 3200–3500 m above sea level, to less than 150 m elevation westward towards the city of Karakul. In the Zarafshon mountain gorges, below 1500 m there are small areas of semi-savannahs as well as mountain forests.

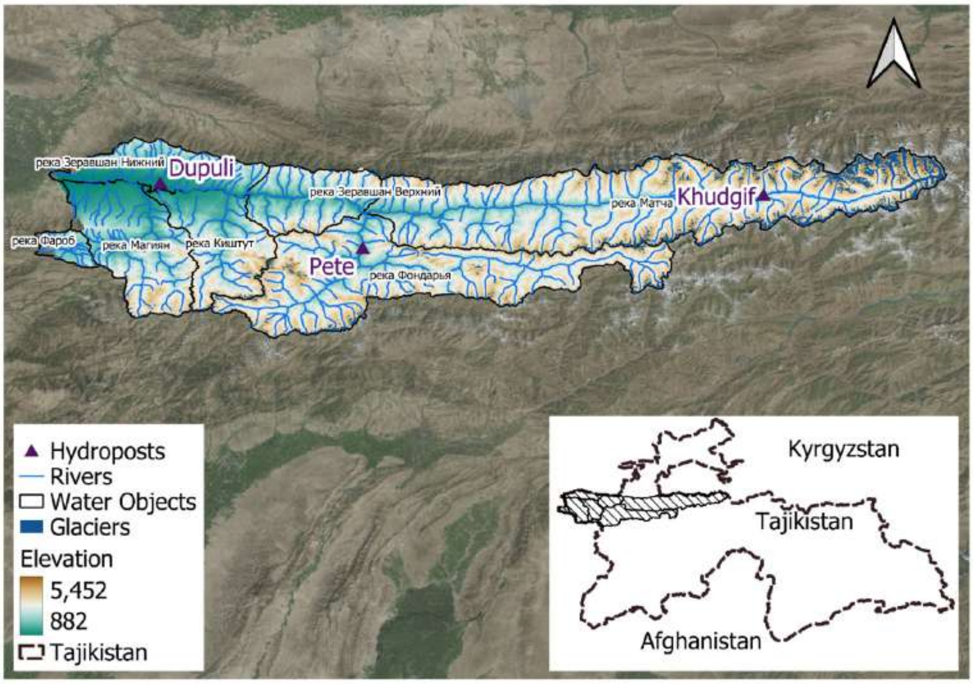


Figure 39. ZRB(ZRB), its tributaries, and water objects. The purple triangles are the discharge stations or 'hydroposts' that have data available after the year 1991. These stations are used to calibrate the hydrological models in this study.

12 This section is based on Abdushukurov et al., 2022.

The ZRB encompasses a total glacier area of 437.9 km^2, with the Zarafshon glacier being the largest among the 632 glaciers. This glacier stretches over 27.8 km in length and covers an area of 87.2 km^2. Data from the Agency of Hydrometeorology of the Republic of Tajikistan reveals significant changes in the Zarafshon glacier's geometric dimensions and mass loss between 1927 and 1991. From 1991 to 2001, the glacier experienced a retreat rate of 88–94 m/year, resulting in a reduction of area by 700,000 m^2. Projections indicate that the glacier's area may further decrease by 30–35% by 2050.

Originating from its source (i.e. Zarafshon glacier), the river flows westward with a gradient of 5.1% over a distance of 260 km, traversing a canyon-like valley carved by two mountain ranges, forming what is known as the Matcha River (Groll et al., 2013). Near the town of Aini, it merges with the Fondarya River, originating from the south, and becomes known as the Zarafshon River (Figure 40). As it continues downstream from Aini, the valley widens, and the gradient decreases to 3.3%, while the slopes of the surrounding mountains become less steep. This part of the catchment area is characterized by small-scale agriculture and a higher population density.

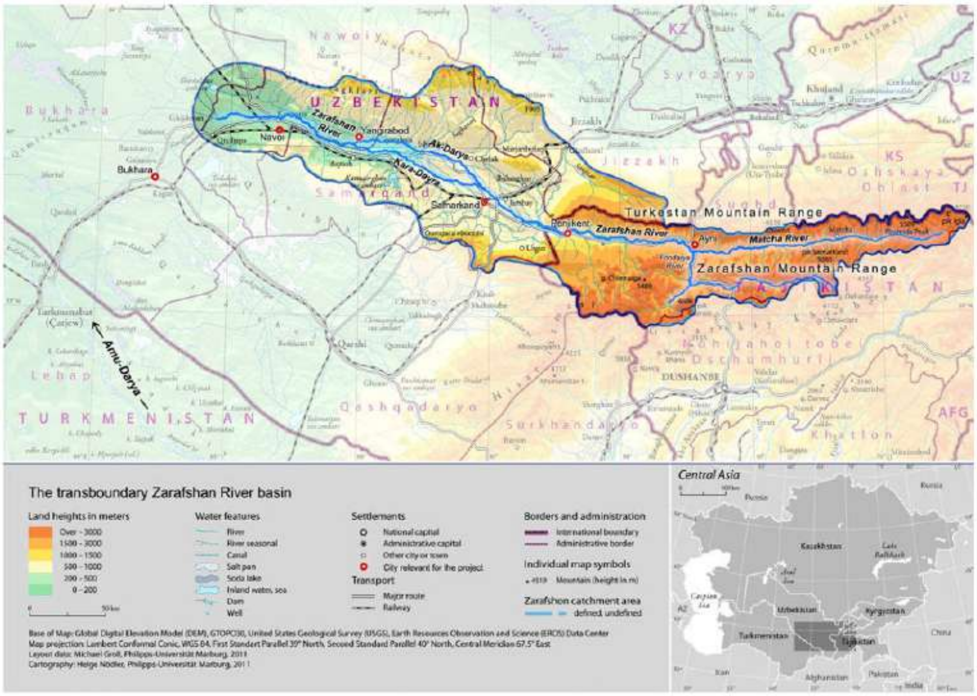


Figure 40. ZRB(ZRB) including the downstream Uzbekistan parts (Groll et al., 2013)

After traveling 170 km, the river enters Uzbekistan downstream of Panjakent, reaching the lowlands of the Aral Sea basin. Passing through a flat region and crossing the Tajikistan-Uzbekistan border, it flows through Samarkand and Bukhara before vanishing in the desert near Karakul, without reaching the Amu Darya River. The landscape flattens notably after Panjakent, with a 1.5% average gradient in the Uzbek segment. The warm climate and flat terrain encourage intensive irrigation agriculture, mainly supported by water diverted into the Bulungur and Dargom canals upon crossing the border. Upon reaching Samarkand, the river splits into two branches—the Ak-Darya in the north and the Kara-Darya in the south—undergoing further diversions. Reservoirs such as Kattakurgan and Akdarya regulate water availability for irrigation, forming the largest freshwater body in the catchment area.

The Zarafshon river maintains an average long-term water discharge of 158 m³/s, with an average long-term runoff of approximately 5 km³ at Panjakent, just before the border between Tajikistan and Uzbekistan[13]. The Zarafshon river, once a crucial tributary of the Amu-Darya serving over six million people in Tajikistan and Uzbekistan, no longer reaches the Amu-Darya due to extensive irrigation water extractions (UNEP, 2011). Its waters sustain households, support economic activities, and fulfil agricultural demands (0.5 million ha) in the region (Figure 41).

Figure 41. Downstream water use of Zarafshon River (Source: Climate Change and Hydrology in Central Asia: A Survey of Selected River Basins)

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A1.2 Climate

Central Asia, encompassing Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, Turkmenistan, and Afghanistan, experiences a notably continental climate. Over half of the annual precipitation occurs as snow during the prolonged winter season (November–March, or cold season), primarily in the cold mountainous regions. This snowmelt subsequently provides irrigation water during the spring and summer months, facilitating agriculture across the extensive cultivated areas along the Syr Darya and Amu Darya River systems.

13 This section is based on Abdushukurov et al., 2022

The predominant characteristics of Tajikistan's climate include aridity, extreme temperatures, and significant intra-annual, inter-annual, and regional variability. In general, Tajikistan's climate is highly continental, resulting in significant seasonal temperature and precipitation variations (Aalto et al., 2017) (Figure 42). During winter, Tajikistan's western regions are exposed to humid Mediterranean and Caspian winds, while in summer, the southwestern areas are affected by dry heat waves from the deserts of Afghanistan, Turkmenistan, and Uzbekistan. These climatic factors result in considerable spatial temperature variations and differences in climate types between the western and eastern parts of the country.

The annual mean temperature ranges from below -20°C in the high-altitude eastern regions to above 15°C in the western lowlands, reflecting a strong influence of elevation on temperature patterns (Figure 42, top panel). During summer, temperatures peak in the western lowlands and valleys, exceeding 25°C and reaching up to 29.7°C, while the eastern highlands remain cooler, with temperatures below 10°C (Figure 42, bottom left panel). In winter, extreme cold dominates the eastern mountainous areas, where temperatures drop below -15°C and even below -20°C in some regions, whereas the western lowlands experience milder winters, with temperatures ranging from -7°C to 5°C.

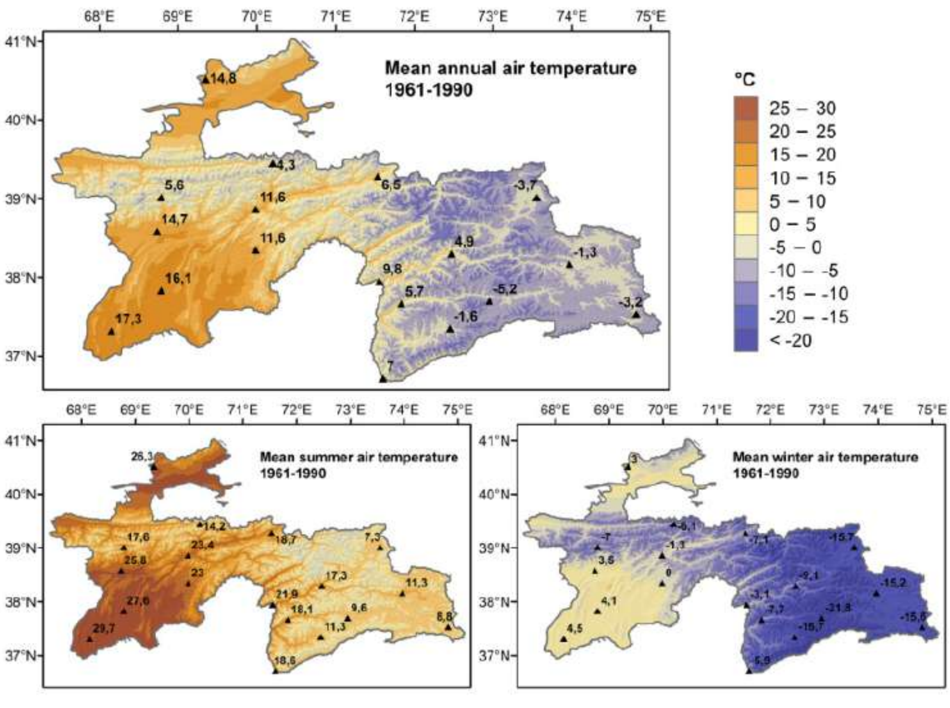

Figure 42. Mean air temperature of Tajikistan based on observed in-situ data from 1961–1990 for annual (top), summer (bottom left, June–August) and winter(bottom right, December–February) time scales (source Aalto et al., 2017).

Most of the annual precipitation occurs during the winter and spring seasons (Figure 43). The mean average yearly rainfall of the ZRB is 500 mm. The annual precipitation of the ZRB is lower compared to other river basins in the region, including the Amu Darya (678 mm), Syr Darya (941 mm), and Indus (837 mm) river basins. (Khanal et al., 2023). The annual precipitation map shows significant variability, with the highest values exceeding 1000 mm in the mountainous regions, particularly in the central and southeastern areas (Figure 43, top panel). Lower precipitation, below 200 mm, is observed in the western lowlands and eastern regions. The summer precipitation map (Figure 43, bottom left panel) indicates generally low precipitation across the country, with most areas receiving less than 100 mm, particularly in the west and lowland regions.

The spring precipitation map (Figure 43, bottom right panel) highlights spring as the wettest season, with precipitation exceeding 800 mm in the mountainous areas. Moderate rainfall (200–600 mm) dominates much of the central and northern regions, while the western and eastern lowlands receive less than 200 mm.

It is expected that there will be less snow and more rain in the future. This is primarily due to warming, which will result in a decrease in solid precipitation (snow) as temperatures become too warm for snow formation, and an increase in liquid precipitation (rain) in the future.

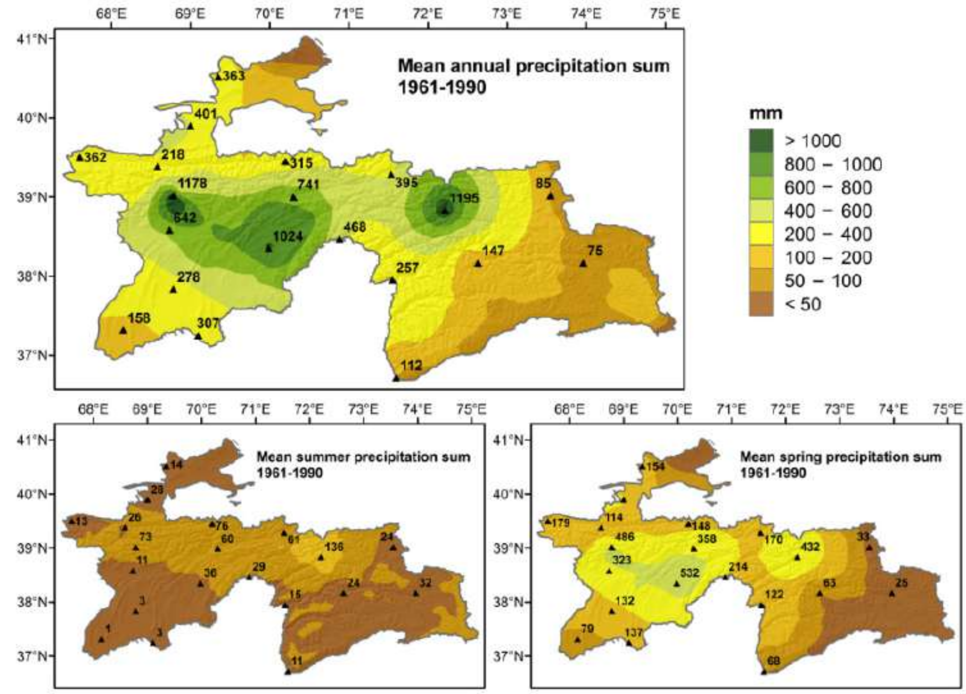

Figure 43. Precipitation of Tajikistan based on observed in-situ data from 1961–1990 for annual (top), summer (bottom left, June–August) and spring (bottom right, March–May, the wettest season) time scales (source Aalto et al., 2017).

Currently, an average temperature of about 5°C is recorded around the Zarafshon glacier, but it is anticipated that it will increase to 8°C or even 10-12°C in the future if warming occurs (Aalto et al., 2017).

Likewise, Normatov et al., (2018) based on the temperature station data near the Zarafshon Glacier found that the recent period (1981–2011, Figure 44 (a)) exhibited significantly stronger warming trends compared to the historical period (1931–1961) (Figure 44 (b)). With the warming trend, the glaciers will shrink, and there will be a reduction in snow and ice within the region. As a consequence, a decrease in the volume of water flowing into the river is expected. Additionally, an increase in the frequency of potentially destructive flood events in the mountains due to changes in hydrological patterns may be observed.

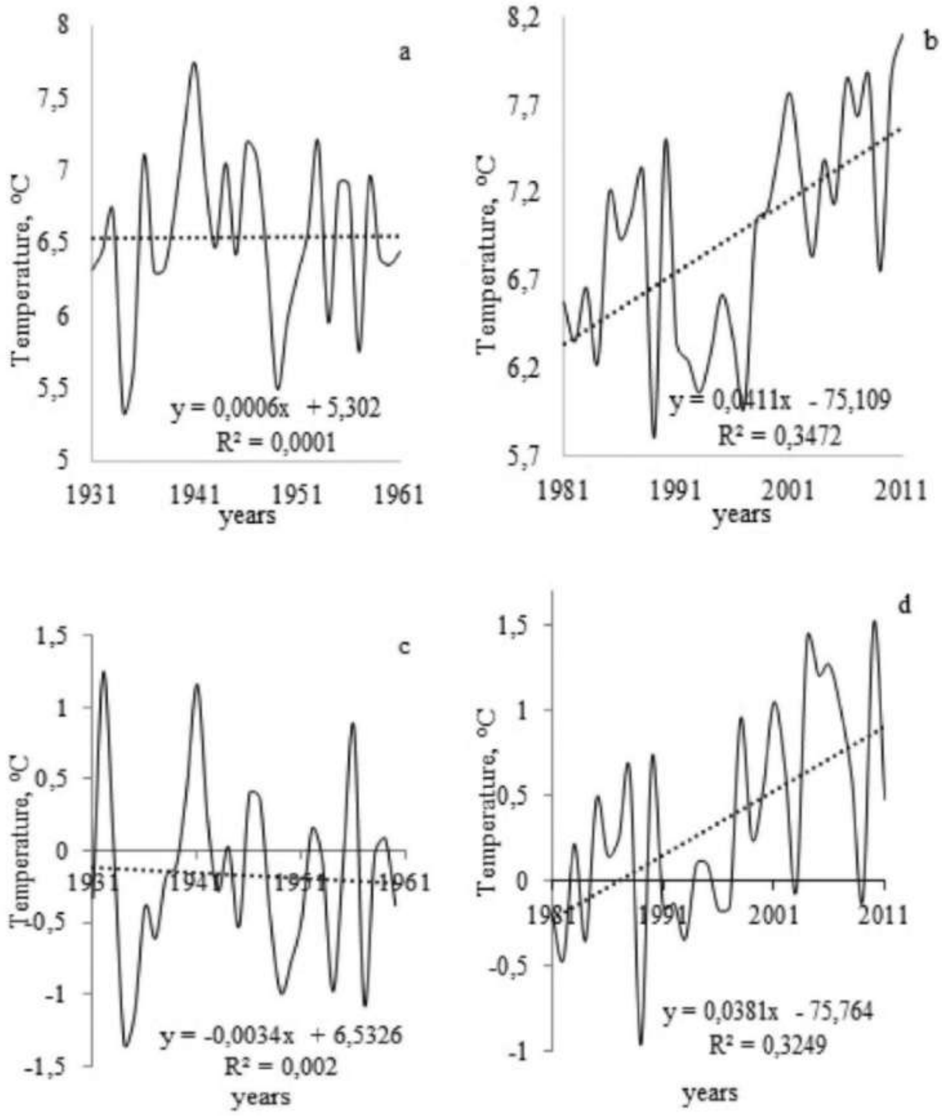

Figure 44. The average annual temperature for the periods of 1931–1961 and 1981–2011 around the glacier Zarafshon (a, b) and in the Yagnob River Basin (c, d) (Source: Normatov & Normatov, (2018)).

The midlatitudes of the Asian continent exhibit two distinct climatic regions: (1) humid eastern Asia, influenced by monsoon circulations, and (2) arid central Asia, characterized by the midlatitude westerlies. The latter serves as a crucial connection between the northern high latitudes, the North Atlantic, and the East Asian monsoon region (Lu et al., 2020).

The climate of the ZRB is thus shaped by these two-circulation systems. Precipitation amounts vary significantly along the West-East transect in the ZRB (Figure 45a). The northern and northwestern regions are drier compared to the wetter southern part. The differences in precipitation patterns are attributed to the steep topography of the region. The Alay, Tian Shan, Pamirs obstructs the orographic influence of precipitation in the east and north-south transect thus making the eastern and northeastern regions wetter. **As a result, the precipitation within the ZRB shows a high annual variability of the precipitation ranging from 1750 mm yr-1 in the eastern and southern parts to 500 mm yr-1 in the western parts** (Figure 45a; Figure 45c).

The years 1998 and 1995 received the maximum and minimum annual precipitation of about 1500 mm and 975 mm, respectively. There are significant negative trends (~ -3 mm) for the basin aggregated annual precipitation in the ZRB (shown by the red dashed line). The precipitation has decreased by ~94mm over the period of 30 years. The ZRB also shows high monthly variability of the precipitation (Figure 45e). The months of March and September receive the maximum and minimum precipitation of about 141 mm and 58 mm, respectively. **The spring season (March through May) dominates the seasonal precipitation distribution and comprises 34% of the annual precipitation.**

The eastern region is colder compared to the western parts (Figure 45b). The basin shows a high annual variability of the annual average temperature ranging from -7.5 to 15.4 °C (Figure 45d). 2016 and 1996 are the hot (3.4 °C) and the cold (1.3 °C) years, respectively. In contrast to precipitation, the annual average temperature shows a visible significant increasing trend of 0.03 °C yr-1. This cumulates to a 0.9 °C temperature rise in the basin over the past 30 years. **The monthly temperature shows a distinct seasonal cycle where the temperature is higher for the summer months (June-August) compared to the winter months** (Figure 45f). The average temperature is highest for July (11.9 °C) and lowest for January (-5.7 °C). The largest variability in the basin aggregated monthly average temperature is found in the winter months (December, January, and February).

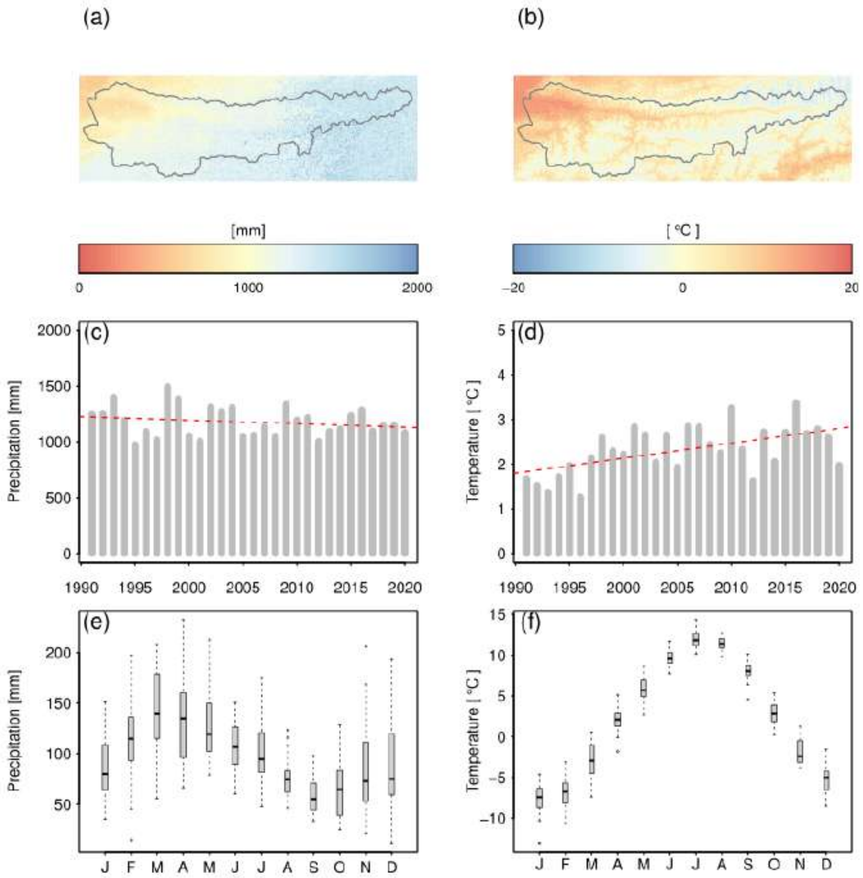

Figure 45. The historical downscaled climate (ERA5 with TopoSCALE) of the ZRB model domain for the baseline period (1991–2020). (a) mean annual precipitation, (b) average temperature, (c) mean annual average precipitation aggregated over the domain, (d) mean annual average temperature aggregated over the domain, (e) climatology of the precipitation, and (f) climatology of the average temperature.

A1.3 Hydrology

In the distant past, the Zarafshon was a tributary of the of the Amu Darya[14]. As a result of the development of irrigation, the two rivers are no longer connected. The source area of the river is largely in Tajikistan, while the densely populated areas with irrigated oases are in Uzbekistan. Before joining the Fondarya the Zarafshon is called the Matcha. The average annual discharge reaches 154 m^3/s, while its average annual volume of discharge is 4.9 km^3 (specific location is not mentioned in the original document). The peak of discharge is June to August, with the maximum in July.

The Zarafshon river and its tributaries are fed by glaciers and snow melt. An analysis of river dynamics for the period 1934 – 1994 did not reveal any significant changes. Between 1995 and 2005 no data were available by unknown reasons. When data started being produced again between 2005-2010 discharge had reached 200-250 m3/s considerably above the average. The hydrological data for the tributaries of the Zarafshon river (the Magiyandarya and Fondarya) do not show any significant trends between 1940- 2010. A review of the most recent period (1972- 2012) shows an increase in discharge of the Zarafshon river and its tributary the Magiyandarya. The reasons are not given by the original documents, but most likely changes in precipitation patterns are behind this.

The total area of the glaciers in the ZRB is 437.9 km^2. The Zarafshon glacier is the largest among the 632 glaciers in Zarafshon with a length of 27.8 km and an area of 132.6 km^2. According to the Agency of Hydrometeorology of the Republic of Tajikistan, there have been significant changes of geometric dimensions and mass loss of Zarafshon glacier during the period 1927–1991. The glacier retreated 88–94 m/year for the period 1991–2001 and its area decreased by 700,000 m2 and it is expected to decrease by 30–35% by 2050[15].

The average annual water discharge of the Zarafshon river for the periods 1931–1961 and 1981–2011 is presented in Figure 46. The decreasing trend of water discharge for the period 1931–1961 can be explained by the low and near-constant value of the temperature resulting in the snow accumulating and expanding the glacier rather than melting and contributing to river flow. This interpretation is supported by the fact that looking at Yagnob River water flow only has been almost constant during period 1931–1961 (Figure c). A completely different pattern in runoff is observed for the period 1981–2011 which experienced a significant increase in water discharge (Figure b). This hypothesis is also supported by looking at the monthly flows (Figure 47).

14 This section is based on Government of Tajikistan, 2014

15 This section is based on Abdushukurov et al., 2022

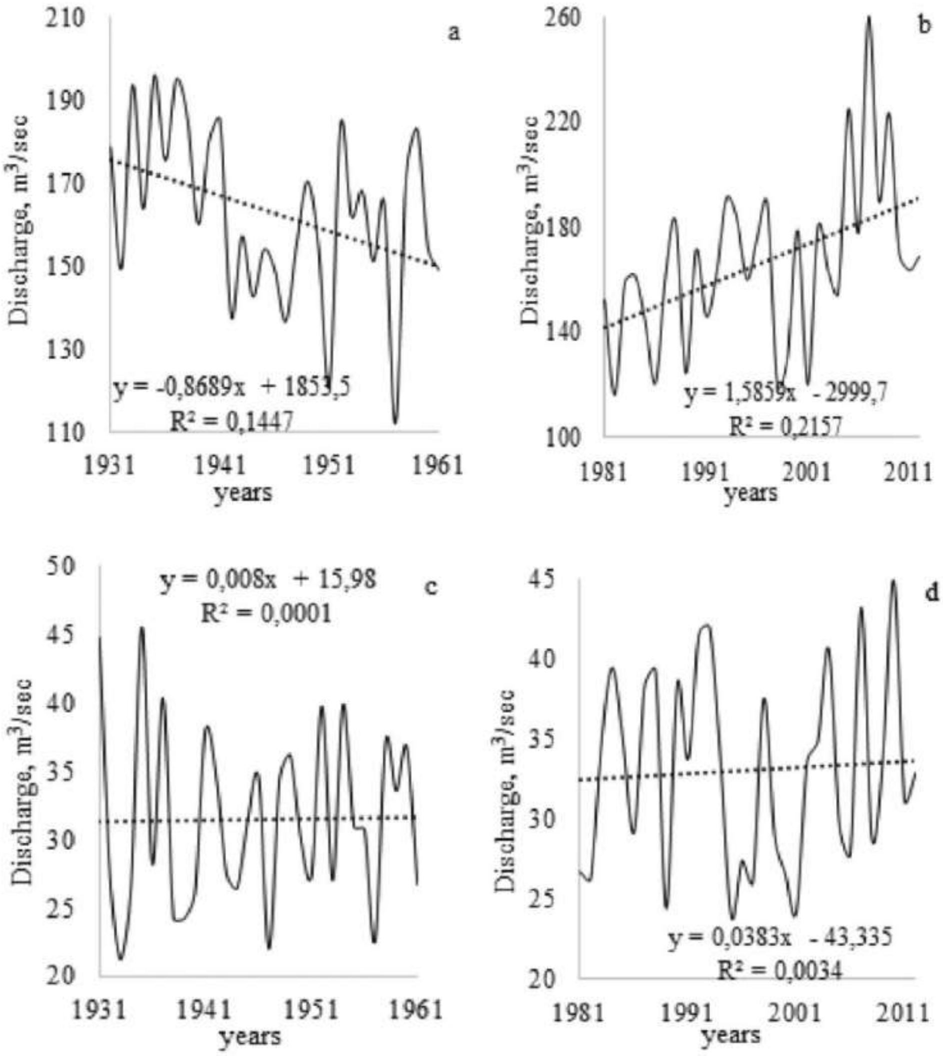

Figure 46. The water discharge value of the Zarafshon (a, b) and Yagnob (c, d) Rivers for the periods 1931–1961 and 1981–2011. Source: (Normatov & Normatov, 2018)

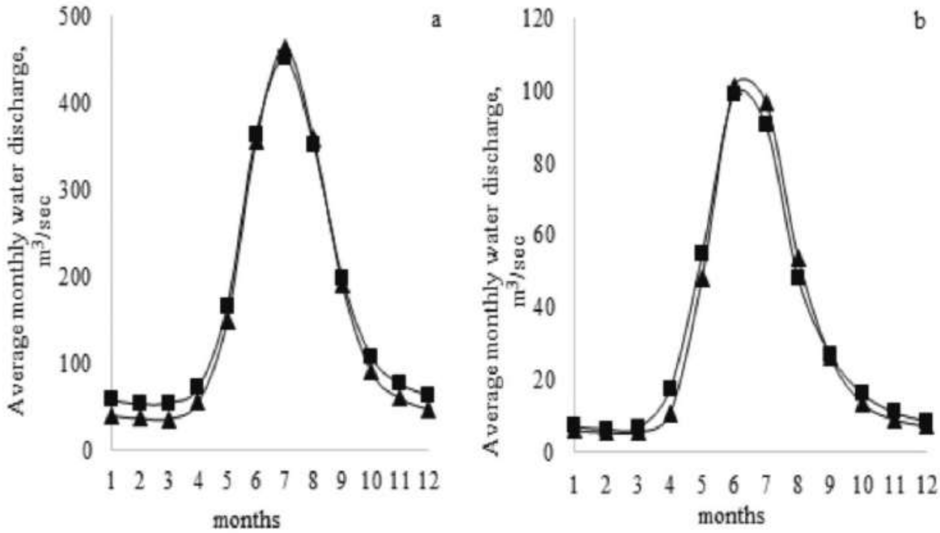

Figure 47. The hydrograph of the Zarafshon (a) and Yagnob (b) rivers for the periods 1931–1961 (▲) and 1981–2011(■). Source: (Normatov & Normatov, 2018)

ANNEX 2: EXPLANATION OF THE MODEL, DATA AND METHODOLOGIES

A2.1 SPHY model

SPHY is a spatially distributed leaky bucket type of model and is applied on a cell-by-cell basis. The main terrestrial hydrological processes are described in a conceptual way so that changes in storages and fluxes can be assessed adequately over time and space. SPHY is written in the Python programming language using the PCRaster dynamic modelling framework (Karssenberg et al., 2010).

SPHY is grid-based, and cell values represent averages over a cell (Figure 48). For glaciers, sub-grid variability is considered: a cell can be glacier free, partially glacierized, or completely covered by glaciers. The cell fraction not covered by glaciers consists of either land covered with snow or land that is free of snow. Land that is free of snow can consist of vegetation, bare soil, or open water. The dynamic vegetation module accounts for a time-varying fractional vegetation coverage, which affects processes such as interception, effective precipitation, and potential evapotranspiration.

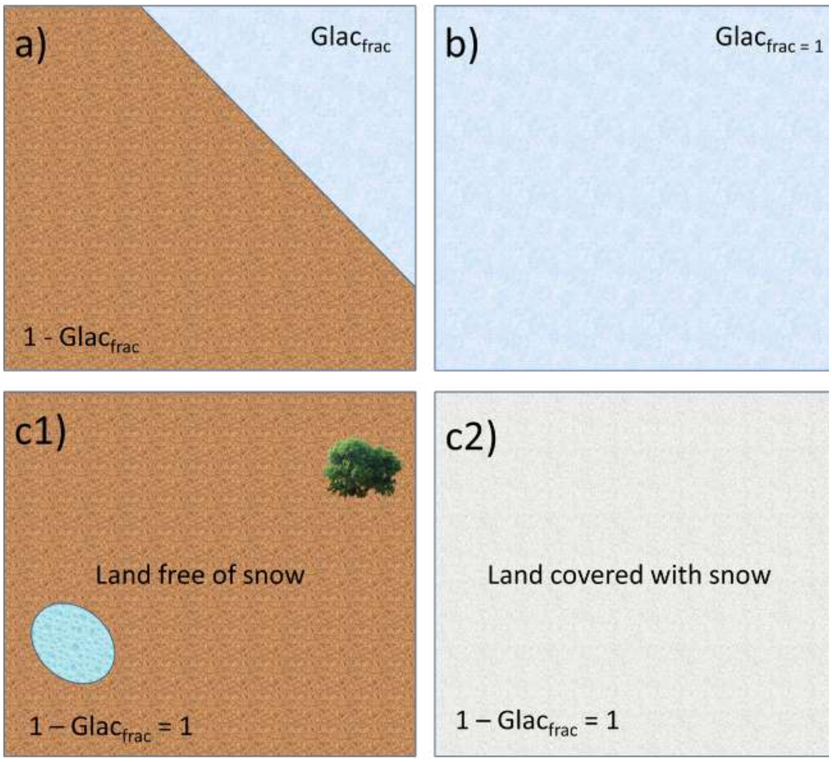

Figure 48. Illustration of SPHY sub-grid variability. A grid cell in SPHY can be (a) partially covered with glaciers, or (b) completely covered with glaciers, or (c1) free of snow, or (c2) completely covered with snow. In the case of (c1), the free land surface can consist of bare soil, vegetation, or open water.

Figure 49 provides a schematic overview of the SPHY modelling concepts.

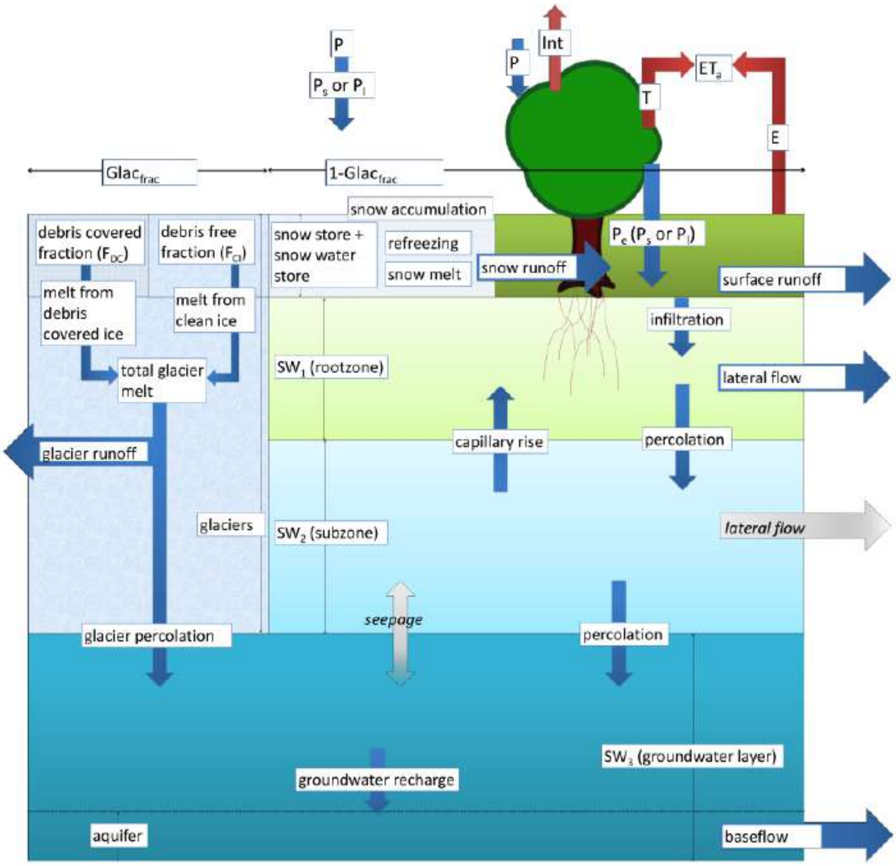

Figure 49. SPHY modeling concepts. The fluxes in grey are only incorporated when the groundwater module is not used.

The soil column structure is similar to the one proposed in Liang et al., 1994, with two upper soil storages and a third groundwater storage. Their corresponding drainage components are surface runoff, lateral flow and baseflow. SPHY simulates for each cell precipitation in the form of rain or snow, depending on the temperature. Precipitation that falls on land surfaces can be intercepted by vegetation and evaporated in part or whole. The snow storage is updated with snow accumulation and/or snowmelt. A part of the liquid precipitation is transformed in surface runoff, whereas the remainder infiltrates into the soil. The reference evapotranspiration is calculated using the Modified Hargreaves reference evapotranspiration method (Hargreaves and Samani, 1985).The resulting soil moisture is subject to evapotranspiration, depending on the soil properties and fractional vegetation cover, while the remainder contributes to river discharge by means of lateral flow from the first soil layer, and baseflow from the groundwater layer. The lateral flow, ground water storage, baseflow and their interaction are calculated as described in (Terink et al., 2015).

Melting of glacier ice contributes to the river discharge by means of a slow and fast component, being (i) percolation to the groundwater layer that eventually becomes baseflow, and (ii) direct runoff. The cell-specific runoff, which becomes available for routing, is the sum of surface runoff, lateral flow, baseflow, snowmelt and glacier melt.

If no lakes are present, then the user can choose a simple flow accumulation routing scheme: for each cell, the accumulated amount of water that flows out of the cell into its neighbouring downstream cell is calculated. This accumulated amount is the amount of water in the cell itself plus the amount of water in upstream neighbouring cells of the cell and is calculated using the flow direction network. If lakes are present, then the fractional accumulation flux routing scheme is used; depending on the actual lake storage, a fraction of that storage becomes available for routing and is extracted from the lake, while the remaining part becomes the updated actual lake storage. The flux available for routing is routed in the same way as in the simple flow accumulation routing scheme.

The model source code is in the public domain (free access) and can be obtained from the SPHY model website free of charge (http://www.sphy-model.org).

The three peer-reviewed open-access publications of the SPHY model can be found at https://doi.org/10.5194/gmd-8-2009-2015 (Terink et al., 2015), Eekhout et al., (2018) and Khanal et al., (2021).

A2.1.1 Dynamic Glacier Module

The model takes sub-grid variability into account to calculate the snow and glacier melt runoff from glaciers (Khanal et al., 2021). By intersecting the glacier outlines, which each have a separate glacier ID, with the model grid the glaciers or parts thereof that lie within each model grid cell are identified (Kargel et al., 2014). Each (part of) glacier is assigned a unique ID. The glacier mass balance of each individual glacier, which can lie in multiple model grid cells is simulated to understand the future changes in glaciers. For each glacier, debris-covered and debris-free parts based is classified based on (Kraaijenbrink et al., 2017a). The initial ice thickness and volume for each glacier parts using data from (Farinotti et al., 2019) are assigned in the next step. For each (part of) glacier the mean elevation from a 30x30 m digital elevation model is calculated (Farr et al., 2007). This is required to lapse daily air temperature from the model grid cell mean elevation to the glacier's mean elevation. Daily precipitation and temperature serve as input for the glacier module to calculate accumulation and melt. The module uses a degree-day approach to calculate the glacier ice melt with a degree-day approach (Hock, 2003). Different calibrated melt rates are applied to debris covered and debris free glaciers (Bolch et al., 2012; Gardelle et al., 2013; Scherler et al., 2011). Future changes in glacier fraction in response to the precipitation and temperature are considered by using a mass conserving ice distribution approach. The accumulated snow in the accumulation zone is transformed into ice and distributed downwards to the ablation area, at the end of each melting season (1st of October). The net imbalance (I), i.e., the difference in the volume of total snow accumulated (SnowS) and total volume of melt generated from the glaciers (GM), forms the basis of ice redistribution.

1. $$I_{n,j} = \mathrm{SnowS}_{n,j} - GM_{n,j}$$

Where the subscript n is glacier id and j is a unique id. If the net imbalance is negative, then the volume of ice is redistributed (Vred) over the ablation zone.

$$2. \qquad Vred_{n,j} = \begin{cases} 0 & , \quad j\epsilon B_{n,j} \\ \sum_{j\epsilon B_{n,j}} I_{n,j} \times \frac{Vini_{n,j}}{\sum_{j\epsilon A_{n,j}} Vini_{n,j}}, & \quad j\epsilon A_{n,j} \end{cases}$$

Where Aj's are the parts of the glacier with negative imbalance, Bj's are the parts of the glacier with a positive imbalance in any glacier id n. The redistribution is proportional to the initial total volume of ice (Vini). i.e., glacier parts with a larger initial ice volume will receive a large volume of accumulated ice from the accumulation zone to the ablation zone. The ice redistribution is done once a year (1^{st} of October) at the end of the hydrological year (1^{st} October to 30th September next year).

Similarly, a degree-day approach, with calibrated melt rates, is used to calculate the snow melt. Again, the precipitation and temperature drive the melting conditions. The model also allows refreezing of meltwater back into the snowpack. If the liquid snow exceeds the storage threshold, snow melt is generated.

A2.1.2 Model Setup

We set up a detailed glacio-hydrological model for the ZRB at 500m spatial and daily temporal resolution in this project. The ZRB SPHY model covers the entire Tajikistan part (just downstream of Panjakent city). The ZRB SPHY model enhances our understanding of fluxes at various locations, enabling detailed exploration of hydrological processes. This enables a deeper insight into the influence of different components on regulating future streamflow in a warmer climate. Most importantly, this study will integrate the local scale information (for instance land use characteristics, weather and climate, glacier mass balance, discharge data etc) within the ZRB SPHY model.

A2.1.3 Datasets

SPHY requires static data as well as dynamic data. For the static data, the most relevant are digital elevation model (DEM), land use type, glacier cover (including differentiation in debris-free and debris-covered ice surfaces), lakes/reservoirs and soil characteristics. The main dynamic data consist of climate data, such as precipitation, temperature, and reference evapotranspiration. Since SPHY is grid based, optimal use of remote sensing data and global data sources can be made. For example, the Normalized Difference Vegetation Index (NDVI) (Tucker 1979; Carlson and Ripley 1997; Myneni and Williams 1994) can be used to determine the leaf-area index (LAI) in order to estimate the growth stage of land cover.

Digital elevation model

The 1 arcsec (~30 m) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data are used (Farr et al., 2007). The DEM is resampled to 500 m for the ZRB SPHY model.

Land use

Land use data used in the ZRB SPHY model are derived from the European Space Agency Climate Change Initiative (ESA CCI) data set (Kirches et al., 2014). The land use map is available for 300m resolution which is resampled to 500m for the ZRB SPHY (Figure 50).

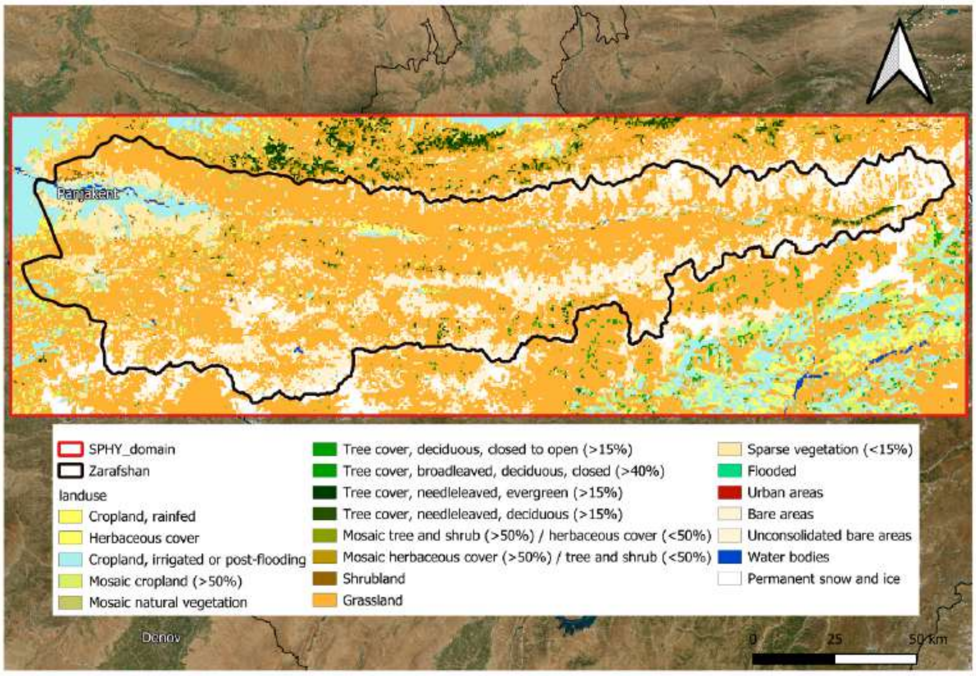

Figure 50. Land use map derived from ESA CCI for the Zarafshon River Basin. The color scheme of the maps is like ESA CCI[16].

Table 17. Land use classes and its description for the ZRB SPHY model domain.

Class	Description	Area (Km²)	Total Area (%)
10	Cropland, rainfed	663.8	2%
20	Cropland, irrigated or post-flooding	1981.0	7%
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	621.0	2%
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	672.8	3%
130	Grassland	14469.0	54%

16 https://climate.esa.int/en/projects/land-cover/data/

150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	1096.8	4%
200	Bare areas	4364.5	16%
220	Permanent snow and Ice	1559.8	6%
—	Others land use type		6%

Soil

Hydraulic soil properties used in this study were derived from HiHydroSoil (250m) and resampled to ZRB SPHY model resolution (Simons et al., 2020).

Glacier mass balance

We used altitudinal Surface Mass Balance (SMB) of four of the major glaciers, Zarafshon glacier (Glacier ID 1317829), Rama glacier (Glacier ID 1322248), glacier Rossnich (Glacier ID 1322829), and Shakhisafid glacier (Glacier ID 1322898) in the basin (Figure 51). Altitudinal SMB is determined following the method used by Miles et al., (2021), solving the continuity equation, supposing that englacial and basal mass changes are not significant, and that firn[17] densification rates are constant. The ice flux divergence is calculated using ice thickness data (Farinotti et al., 2019) and observed ice surface velocity data from 2016 to 2017 (Millan et al., 2022), then filtered using an ice thickness-dependent spatial filter of the flux divergences (Van Tricht et al, 2021). Measurements of surface elevation change are used to calculate the 2015–2019 SMB across various areas and altitudes, making sure to consider any uncertainties in the data and methods (Hugonnet et al., 2021). Uncertainties in the accumulation area are much larger due to the large uncertainties in the underlying datasets; the firn (snow older than 1 year) densification assumption is also not likely to be valid in this domain.

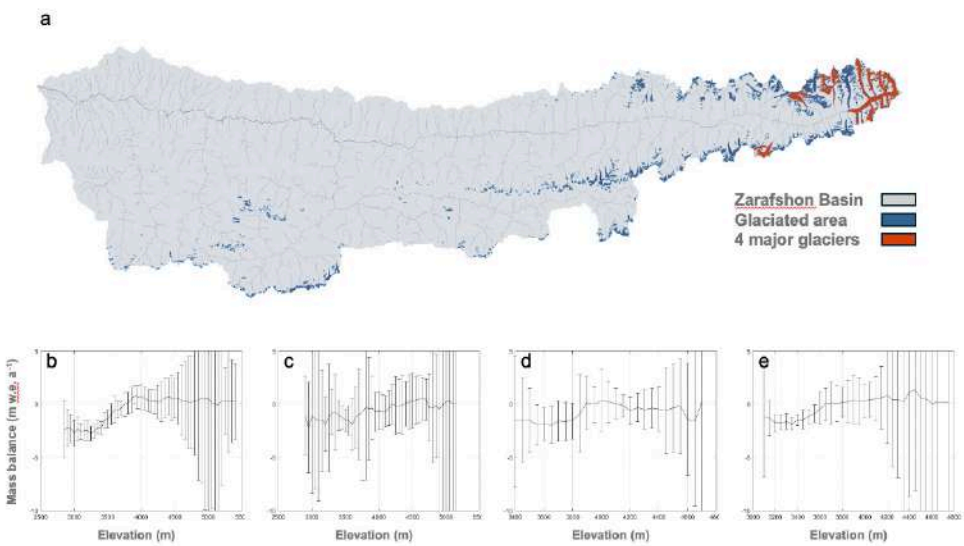

Figure 51. The glaciated area in ZRB(a). Glacier mass balance at different elevation bands for Zarafshon glacier (b), Rama glacier (c), Rossinch glacier (d) and Shakhisafid glacier (e).

17 Firn is a type of snow that is one year old.

Snow cover

The 500 m resolution MODIS MOD10A1 (hereinafter MODIS) daily snow cover data (2000–2020) is used to calculate the monthly snow persistence (Hall and Riggs, 2015) for the ZRB SPHY model as shown in Figure 52.

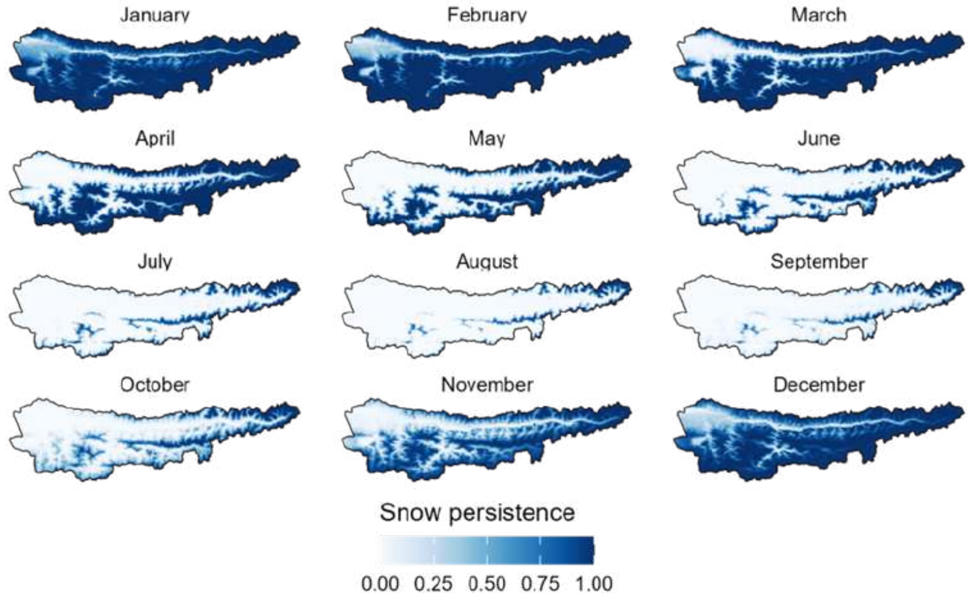

Figure 52. Monthly climatological snow persistence maps from MODIS for the period 2000–2020 used for calibration of simulated snow cover using ZRB SPHY model.

Meteorological data

The meteorological forcing for SPHY has been provided by the topography-based downscaling scheme TopoSCALE (Fiddes and Gruber, 2014). TopoSCALE downscales atmospheric fields available on pressure levels to a high-resolution digital elevation model. In this case, the atmospheric model data is provided by the latest generation of ECMWFs reanalysis product, ERA5 (Hersbach et al., 2020).

TopoSCALE performs a 3D interpolation of atmospheric fields available on pressure levels, to account for time-varying lapse rates, and a topographic correction of radiative fluxes. The latter includes a cosine correction of incident direct shortwave radiation on a slope, adjustment of diffuse shortwave and longwave radiation by the sky view factor, and elevation correction of both longwave and direct shortwave. It has been extensively tested in various geographical regions and applications, i.e., permafrost in the European Alps (Fiddes et al., 2015), permafrost in the North Atlantic region (Westermann et al., 2015), Northern hemisphere permafrost (Obu et al., 2019), Antarctic permafrost (Obu et al., 2020), Arctic snow cover (Aalstad et al., 2018), Arctic climate change (Vikhamar Schuler and Østby, 2020) and Alpine snow cover (Fiddes et al., 2019). TopoSCALE can therefore provide hillslope scale model forcings without any requirement for ground data by accounting for the main topographic effects on atmospheric forcing. In this project, we developed a plugin for the ZRB SPHY model which produces gridded forcing fields, accounts for projection differences between the target grid and native ERA5

(WGS84) and produces forcing files in SPHY required format. We generated SPHY forcings for the period 1991-2020 and these data have been further used as a baseline dataset with which to downscale CMIP6 climate data.

Streamflow

There are 28 discharge stations (or hydroposts) in the ZRB. However, most of the stations have either data till the 1980s or they are on the tributaries of the main Zarafshon River. Only a few stations have discharge for the recent years.

As shown in Table 18, three stations were selected in this study to calibrate and validate the SPHY and WEAP models. Two of the stations are located in the main Zarafshon river and the third one is located in a tributary. The selected stations were Khudgif and Dupuli stations on the Zarafshon River, and the Pete station on the Fondarya River for our calibration and validation efforts. The years 2001–2005 are used as calibration period and the years 2006–2010 as validation period.

Table 18. Observed discharge stations in the ZRB-SPHY model domain

Station	River	Resolution	Start	End	Years	Missing data (%)
Khudgif	Zarafshon	daily	2000	2010	11	0
Pete	Fondarya	daily	1991	2017	27	4% (1997)
Dupuli	Zarafshon	daily	1991	2017	27	31% (1993–2005)

A2.1.4 Model calibration and validation

Model calibration is essential in hydrology to ensure that the simulated outputs accurately represent real-world conditions, thereby improving the reliability of water resource predictions and management decisions. This process adjusts model parameters to minimize discrepancies between observed and simulated data, enhancing the model's predictive accuracy (Table 19).

Glacio-hydrological model calibration can suffer from equifinality (Azam et al., 2021), the phenomenon that different parameter combinations can lead to the same simulated discharge pattern. For example, a shortage in snow melt can be compensated by excess glacier melt and lead to the same runoff magnitude and pattern. At the same time, achieving optimal model results given the sparsity of input data in such a remote basin as Zarafshon river basin, requires finding an optimal set of parameters using numerical minimization procedures.

Table 19 Mountain relevant SPHY model parameters along with description units and plausible range.

Parameters	Description	Units	Range
DDFS	Degree day factor for snow	mm °C^{-1} day^{-1}	2 – 11
DDFDG	Degree day factor for debris cover glacier	mm °C^{-1} day^{-1}	2 – 11
DDFG	Degree day factor for Snow for glacier	mm °C^{-1} day^{-1}	2 – 11
Tcrit	Critical temperature	°C^{-1}	-1 – 3
SnowSC	Water storage capacity of snowpack	—	0 – 1
Kx	Routing recession coefficient	—	0 – 1
RootDepthFlat	Thickness of root zone	Mm	50 – 1500
SubDepthFlat	Thickness of subsoil	Mm	50 – 1500
AlphaGw	Baseflow recession coefficient	—	0 – 1
YieldGw	Specific aquifer yield	—	0.01 – 0.5

To avoid the pitfalls of model equifinality, we use a multi-step strategy to understand biases in precipitation, snow, glaciers, and rainfall-runoff processes in the model, to allow for optimal and, importantly, realistic model calibration and selection of the model parameter set (Khanal et al., 2021; Pellicciotti et al., 2012). In this approach, there are three main steps: (i) precipitation correction, (ii) snow and glacier bias evaluation, and (iii) Monte Carlo runoff optimization runs.

Precipitation correction

In mountain regions, precipitation is one of the most uncertain components of the high-altitude water cycle. There is a fundamental lack of precipitation observations in the mountainous part of central Asia. Precipitation at elevations above 3,000 m has only been measured at a few benchmark sites. Most precipitation gauges in the region are located in valleys, which are not representative of precipitation patterns at higher altitude. Measurements of precipitation type, amount of snowfall or snow-water equivalent are even scarcer as these require advanced sensors. Moreover, there are no observation-based studies with a design that allows us to systematically analyse the interaction between the extreme topography and precipitation. These data gaps have important ramifications: there is no reference against which models can be evaluated, which results in large uncertainties in most hydrological and climate change impact studies.

Commonly used gridded precipitation datasets are very inaccurate at high altitude and have a resolution that is much too coarse for high-resolution hydrological assessments. In this study we use the ERA5 reanalysis dataset. This is a state-of-the-art data set with a resolution of 25 km. However, this is still too coarse for our model application (500 m resolution) and the ERA5 data are further downscaled with TopoSCALE to the model resolution (here after referred to as ERA5-TopoSCALE). Comparison with observations showed strong overestimation of the downscaled ERA5-TopoScale data in the mountainous parts of the ZRB and an underestimation in the lower part towards the border with Uzbekistan.

As a first step in the model calibration and obtaining accurate hydrological model output, we therefore implemented a precipitation bias correction. Since the precipitation observations were also inconsistent, we have based this correction on a comparison between overall observed and modelled river flow. We have implemented a mean annual elevation dependent precipitation correction factor (Figure 53), where precipitation is reduced at lowest elevations with a factor 0.5 and increased at highest elevations with a factor 3. All precipitation input is multiplied with the correction map first, before any other glacier, snow and river discharge calibration.

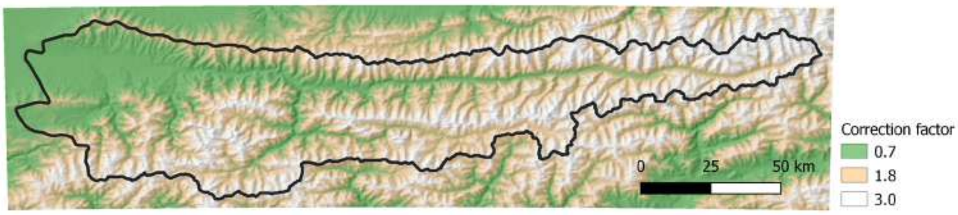

Figure 53. The Precipitation correction factor. The original downscaled ERA5-TopoSCALE precipitation data is divided by this elevation-dependent correction factor

Snow cover bias assessment

The ZRB is highly snow-dominated, and achieving accurate hydrological modeling results in the basin requires a good representation of snow and snowmelt. To optimize snow simulations, we compared the simulated snow cover of ZRB-SPHY simulations with observed snow cover derived from satellite data. The latter was obtained from monthly snow cover climatology derived from daily cloud-masked MODIS data (MOD10A1) for the entire model period for which MODIS data is available, i.e., 2000-2020 (Figure 52).

Temperature bias often exists in reanalysis data, including the ERA5 input used as forcing of SPHY. As temperature is a key component in controlling the temperature index snow modelling principle employed by SPHY, we bias-correct the input temperature (ERA5-TopoSCALE field to achieve proper snow output. We performed this procedure by minimizing the difference between modelled and observed snow persistence, i.e., the fraction of time a location is snow-covered. This bias correction is included as a parameter in the Monte Carlo calibration procedure.

To assess the individual implications or sensitivity of changing the input temperature on the snow simulations, we have evaluated the output of a separate ensemble of specific snow calibration model runs for which the forcing temperature was modulated. For this ensemble, we imposed temperature offsets on the input forcing of –5 °C to +5 °C with steps of 0.5 °C.

Glacier surface mass balance bias assessment

To calibrate the ZRB-SPHY model, we used altitudinal SMB (Surface Mass Balance) of four major glaciers in the basin. The estimated altitudinal SMB represents the average annual values spanning from 2015–2019, as constrained by the input data on surface elevation change and velocity in that region. We use the ZRB-SPHY model simulation for the same period to calculate the altitudinal SMB and compare it with the observed SMB (Figure 51).

The parameters related to glacier mass balance, i.e., DDFS (degree day factor for snow), DDFG (degree day factor for clean glaciers), DDFDG (degree day factor for debris covered glaciers) were fine-tuned to achieve optimal alignment with observed data

Monte Carlo runoff calibration

Data scarcity in high mountain areas presents significant complications for hydrological model calibration, primarily due to the complex and heterogeneous nature of these environments. Limited availability of hydrometric data, such as streamflow, precipitation, and snowpack measurements, hinders the accurate representation of hydrological processes. Although there is observed discharge from three stations in ZRB, available as well as remote sensing constraints for snow and glacier, it remains challenging to validate and fine-tune models. The spatial and temporal variability of many environmental variables relevant for the hydrological system is simply (largely) unknown.

To achieve optimal model runoff simulations given the available discharge data under realistic parameter conditions, while also constraining it for observed snow and glacier states, we have generated an ensemble of 500 individual model simulations in a Monte Carlo procedure (Mishra, 2009). In the procedure, each model simulation is run with a randomly sampled parameter set, and therefore they all lead to different runoff time series, and snow and glacier simulations. Nine different parameters are sampled stochastically from a truncated normal distribution, i.e. a variant of the regular Gaussian distribution with fixed minimum and maximum values (Geweke, 1998). The parameters and their distribution characteristics are presented in Table 20. The runs in the top ten of best performing objective values (i.e. lowest) were evaluated and the individual run with the most realistic set of parameters from a hydrological perspective was selected as final parameter set for the analysis.

Table 20. Parameters varied in the Monte Carlo procedure and the characteristics of the normal distribution used for each of them.

Model parameter	Mean	Minimum	Maximum	Standard deviation
CapRiseMax	0.5	0	1	0.1
AlphaGw	0.5	0.1	1	0.2
DDFG	4	1	10	2
GlacF	0.4	0	1	0.2

Tcrit	1	-1	3	1
SnowSC	0.3	0	0.6	0.2
SnowF	0.5	0	1	0.2
Tcorr_fact	0	-2	2	0.4
Kx	0.95	0.85	1	0.05

To assess the performance of each individual run within the ensemble of 500 simulations and select the all-round best performing run, we used a combination of weighted hydrological and cryospheric evaluation statistics at each discharge station in an objective function per discharge station. This objective function quantifies the difference between observed and simulated data, and by minimizing the function, we can select the model parameters that allow for optimal alignment between model outputs and real-world observations. The functions of the three stations are then combined using weights in a final basin-wide objective function.

To evaluate streamflow components in the procedure, we use percent bias (PBIAS) and the Kling-Gupta efficiency (KGE) (Gupta et al., 2009; Nash and Sutcliffe, 1970). These indicate absolute cumulative deviations and how well the timing of peaks in the hydrograph match, respectfully. To evaluate glacier SMB performance, we use the total difference in absolute glacier mass balance between the observed and simulated over the entire altitudinal range of Zarafshon Glacier (MBBIAS). Snow cover is evaluated by calculating the sum of normalized climatological snow cover biases for the months March–June and between 1500 and 3500 m elevation (SCBIAS), an indicator of simulated snow cover accuracy in the main snowmelt season.

An objective value is defined for each station using the following objective function that combines the statistics described above. Note that PBIAS, KGE, SCBIAS, and MBBIAS are first scaled from their original values to values in the range 0 to 1:

3. $$O_{\mathrm{s}} = w_1\mathrm{PBIAS} + w_2(1\text{-}\mathrm{KGE}) + w_3\mathrm{SCBIAS} + w_4\mathrm{MBBIAS}$$

where Os is the objective value for each individual station and wn are the weights applied to each of the statistics (Table 21). Each objective value for a station is subsequently combined to a total objective value (O_{tot}) using station specific weights (w_d, w_p, w_k) using:

4. $$O_{\mathrm{tot}} = w_d O_{\mathrm{Dupuili}} + w_p O_{\mathrm{Pete}} + w_k O_{\mathrm{Khudgif}}$$

Table 21. Weights used in the objective functions to give more weight to specific statistics or stations in determining the optimal calibration run.

Component	Weight
w_1	0.7
w_2	1.5
w_3	0.2
w_4	0.5
w_d	1.0
w_p	0.5
w_k	0.5

The runs in the top ten of best performing objective values (i.e. lowest) were evaluated and the individual run with the most realistic set of parameters from a hydrological perspective was selected as final parameter set for the analysis.

A2.1.5 Future Climate change scenarios

Future climate forcings for this study are based on Inter-Sectoral Impact Model Intercomparison Project-ISIMIP3b (Lange, 2021). The ISIMIP offers a framework for gathering consistent climate impact data across various sectors and scales. It provides a unique opportunity to examine interactions between climate change impacts through standardized scenarios.

The ISIMIP3b phase of the third simulation round focuses on quantifying climate-related risks under different levels of global warming and socio-economic changes.

Group I simulations utilize historical climate change data from Coupled Model Intercomparison Projects phase 6 (CMIP6) ensembles, combined with observed historical socio-economic factors.

Group II simulations are based on future climate projections from CMIP6, with socio-economic factors held constant at 2015 levels.

Group III simulations incorporate anticipated changes in socio-economic factors. The observational reference dataset for bias adjustment of ISIMIP3b is W5E5 v2.0 (Cucchi et al., 2020). The bias adjustment method employed is ISIMIP3BASD v2.5.0 (Lange, 2019).

This dataset includes CMIP6-based and bias-adjusted atmospheric climate input data for all three ISIMIP3b simulation groups. It covers five CMIP6 global climate models (GFDL-ESM4,

IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL), five CMIP6 experiments (piControl, historical, SSP126, SSP370, SSP585), and eleven CMIP6 variables (huss, hurs, pr, prsn, ps, rlds, rsds, sfcWind, tas, tasmax, tasmin).

For this project, we used four variables (pr, tas, tasmax and tasmin) and a selection of five CMIP6 GCMs for three future scenarios (ssp126, ssp370, ssp585). SSP126 represents low emissions with strong mitigation efforts, SSP370 represents moderate emissions with some mitigation, and SSP585 represents high emissions with minimal mitigation. The raw ISIMIP3b has been downscaled using innovative trend-preserving methods to align with W5E5, a reference dataset derived from enhanced ERA5 reanalysis data, which shares the same source as the ERA5-TopoSCALE reference forcing (Figure 54).

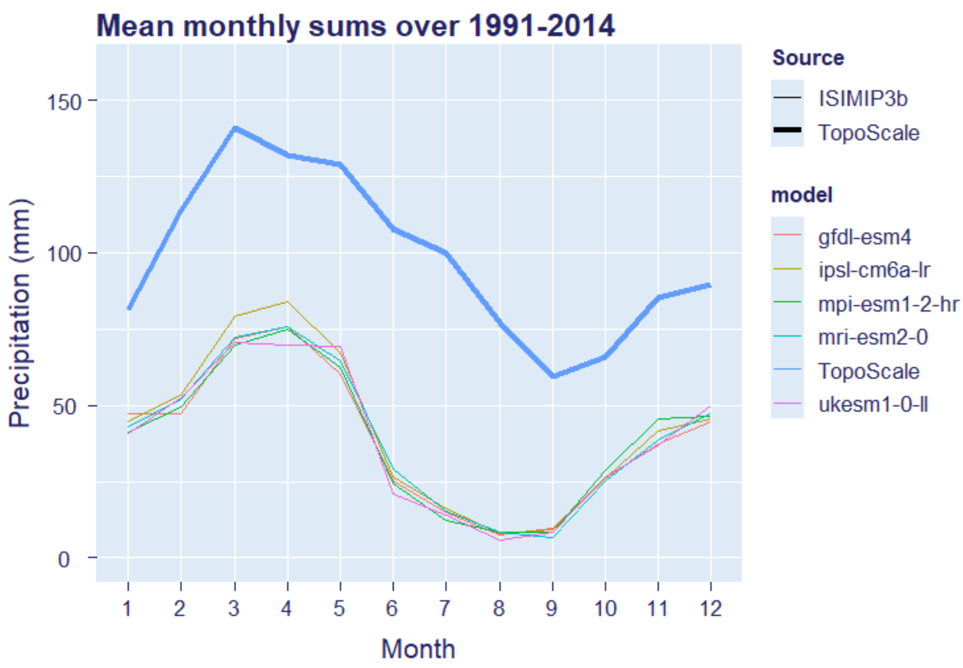

Figure 54. Monthly historical climatological overview of the precipitation of five ISIMIP3b models and ERA5-TopoSCALE forcing.

Downscaling

Downscaling of the ISIMIP3b data was performed by calculating monthly mean deltas between ERA5-TopoSCALE and the baseline scenario of ISIMIP3b over the period 1991–2014. These deltas are subsequently applied to the future daily ISIMIP3b series (i.e. separately to each combination of model (n=5) and scenario (n=3), n=15)), using the delta for the associated month of each specific day of the year (Figure 55).

Since precipitation in summer is relatively low in the ISIMIP3b ensemble compared to the ERA5-TopoSCALE high multiplicative delta factors exist for the summer months (Figure 56). This may cause single extreme events in the future to be greatly exacerbated to unrealistically high magnitude. A maximum precipitation cutoff was therefore applied to the downscaled daily precipitation series, ensuring that the daily precipitation sums could not exceed a value of 2x the maximum daily precipitation sum of the ERA5-TopoSCALE reference for a given month.

Figure 55 illustrates the projected changes (or mean deltas) in the ZRB basin aggregated annual average temperature and precipitation when comparing the end of century horizon (2071–2100) with the reference period (1991–2020). All the climate models predict that the future will be warmer compared to the reference period, although the signals for precipitation changes are mixed. For example, the MPI-ESM1-2-HR model under SSP370 and the DGDL-ESM4 model both project a decrease in precipitation by about 3% and 5%, respectively, by the end of century. In contrast, the UKESM1-0-LL model projects that, under the SSP585 scenario, temperatures will rise by approximately 7.2°C while precipitation is expected to increase by around 23%.

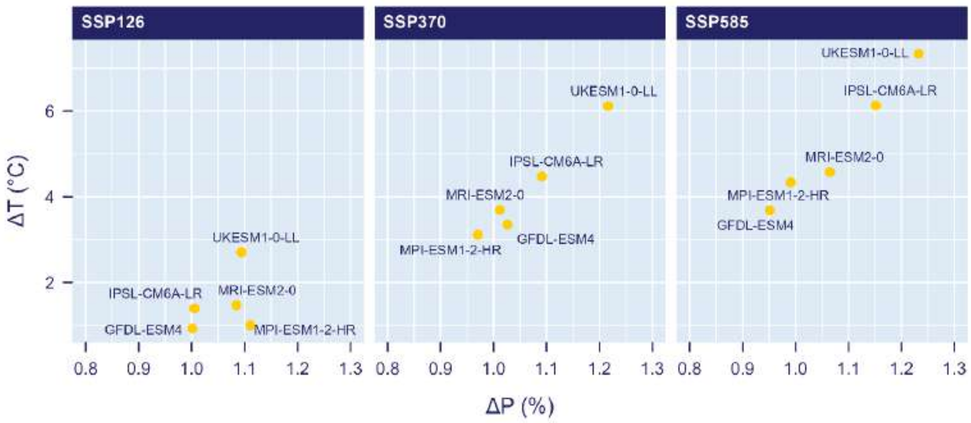

Figure 55. Annual mean deltas for temperature and precipitation between end of century (2071-2100) and reference (1991-2020)

Figure 56 shows the mean monthly differences in both temperature and precipitation when comparing the future period (2071–2100) to the reference period (1991–2020). The temperature increases occur every month, although the magnitude of warming may vary seasonally, suggesting that some months, summer months, warm more than others. In contrast, changes in precipitation are not uniform; some months (i.e., summer) may see increases while others could experience decreases. This monthly breakdown highlights that climate change impacts are seasonally dependent, affecting temperature and rainfall patterns differently throughout the year

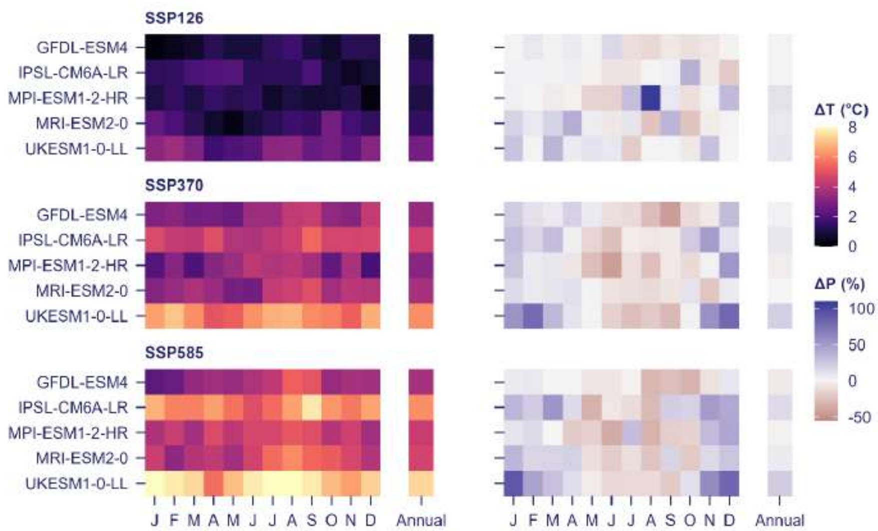

Figure 56. Mean monthly deltas for temperature and precipitation between end of century (2071-2100) and reference (1991-2020).

The annual trends consistently show strong warming across all scenarios, while precipitation increases are marked by greater variability and uncertainty (Figure 57). By century's end, basin-aggregated temperatures are projected to diverge considerably reaching ~9°C under SSP585 compared to ~3.75°C under SSP126.

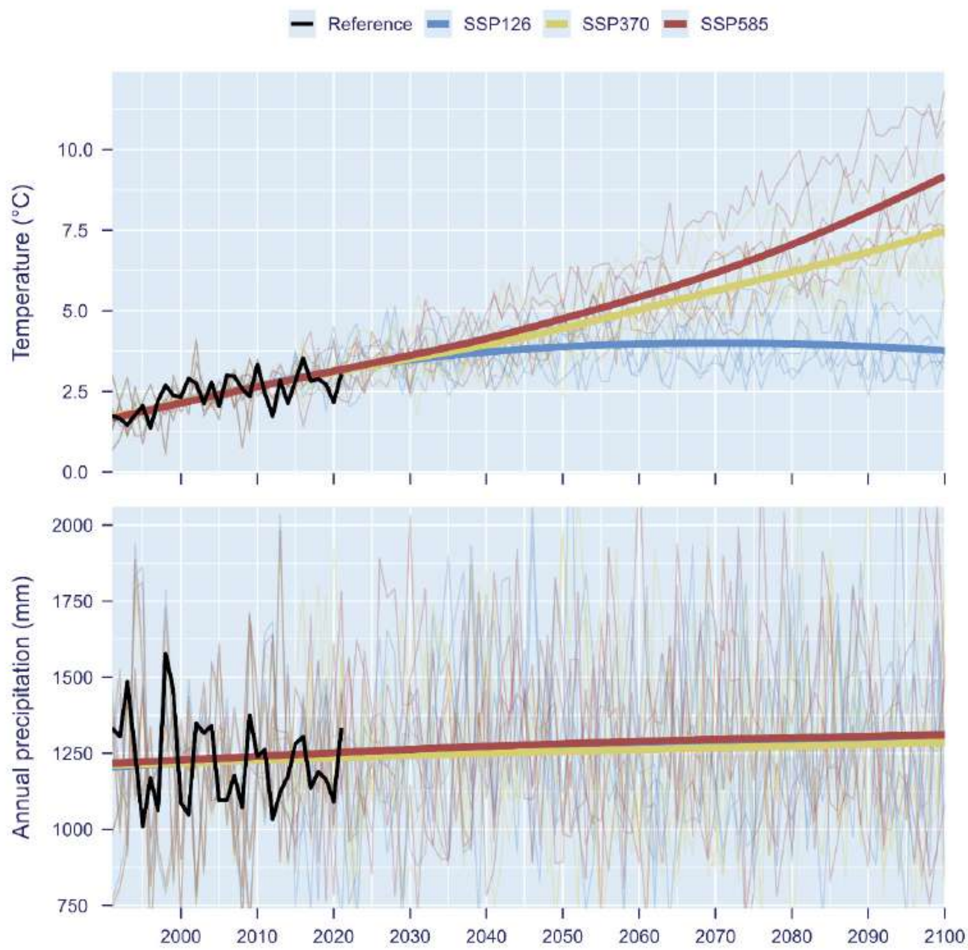

Figure 57. Basin aggregated downscaled future annual temperature and precipitation timeseries and trends for SSP126, SSP370 and SSP585.

A2.1.6 Model Calibration

The final calibrated model parameters after the Monte Carlo procedure and objective function minimization are shown in Table 22.in the Monte Carlo procedure and the characteristics of the normal distribution used for each of them.

Table 22. Final calibrated model parameters with description, units, and values for ZRB-SPHY model.

Parameters	Process	Description	Units	Value
DDFDG	Glacier	Degree day factor for debris cover ice	mm °C^{-1} day^{-1}	4.000
DDFG	Glacier	Degree day factor for clean ice	mm °C^{-1} day^{-1}	4.000

DDFS	Snow	Degree day factor for snow	mm °C^{-1} day^{-1}	1.401
Tcrit	Snow	Critical Snow Temperature	°C	-0.52
SnowF	Snow	Fraction of snowmelt infiltration to soil	—	0.274
SnowSC	Snow	Snowpack water holding capacity	—	0.196
Kx	Runoff	Routing coefficient	—	0.971
Tcorr_fact	Runoff	Temperature correction factor	°C	-0.485
AlphaGw	Runoff	Baseflow days	—	0.508
DeltaGw	Runoff	Groundwater recharge delay time	days	300

The results shown in Figure 58 reflect that the calibrated runs have a slight overestimation of snow cover at mid altitudes in spring (March–May) and an underestimation of snow cover at high altitudes above 3500 m in summer (June–August). Given the total amount of snow in the basin and the model parameterization that is based on a temperature index procedure, the biases are small.

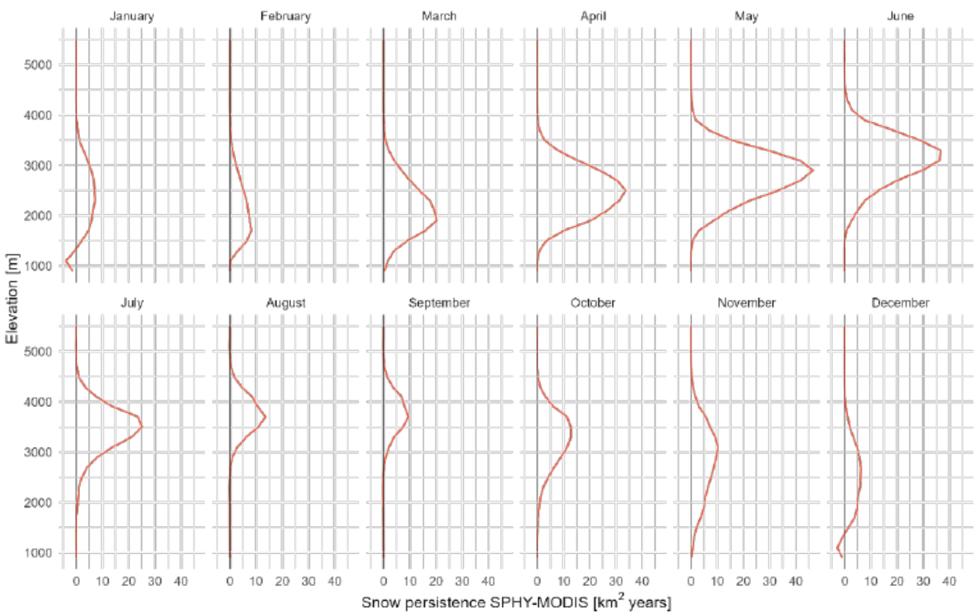

Figure 58. Biases between SPHY and MODIS of climatological snow cover for the period 2000–2020 for each month and along the elevation range for the calibrated model run. The snow cover biases are shown as normalized snow persistence per unit area per unit time.

Calibrated glacier mass balances for four glaciers in Zarafshon Basin show good agreement with observed mass balances (Figure 59) and are mostly within the error range of the observed mass balances. Altitudinal patterns of SMB also correspond well with the observed mass balance gradients. The ZRB-SPHY modelled results show similar altitudinal gradient of modelled SMB as compared to the observations in the upper ablation area, and also identify the inversion of this gradient for the debris-covered area (Bisset et al., 2020).

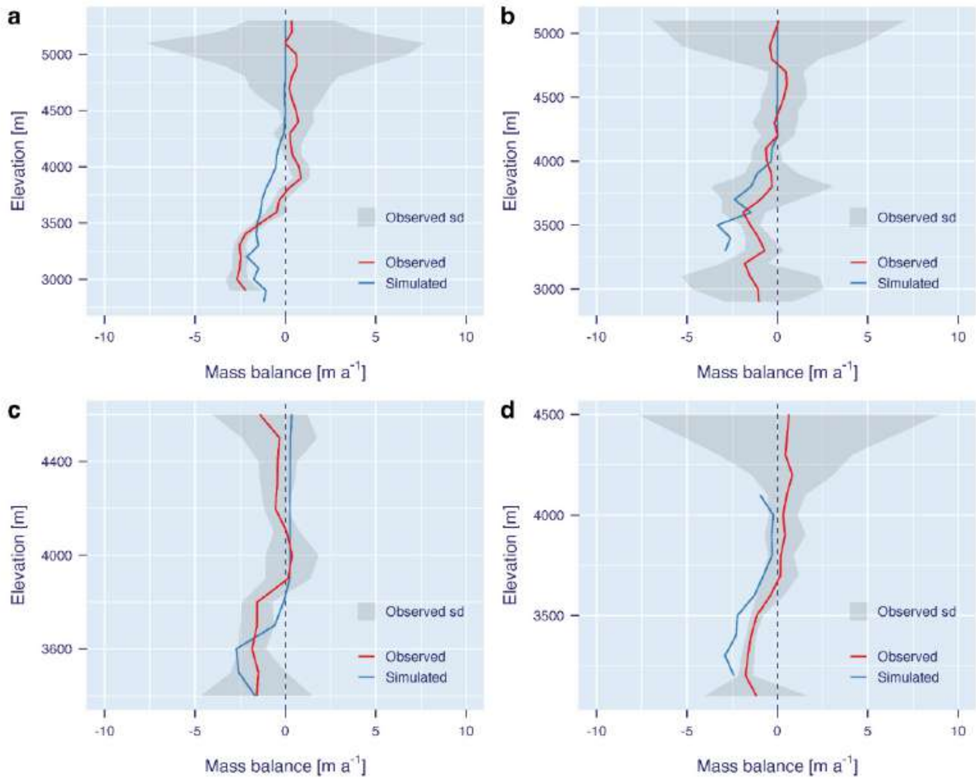

Figure 59. Altitudinal glacier mass balance for the glacier Zarafshon (a), Rama glacier (b), glacier Rossinch (c) and Shakhisafid glacier (d) averaged over the period of 2015–2019. Simulated glacier mass balance from SPHY model (blue) and observed values (red).

Figure 60 regarding the final runoff at the three discharge stations used for calibration (Dupuli, Pete and Khudgif) shows good agreement between observations and model simulations. Performance indicators such as Nash-Sutcliffe efficiency criterion (NSE), percent bias (PBIAS), coefficient of determination (R2), and the Kling-Gupta efficiency (KGE) show good values for most stations. Only the PBIAS for Khudgif is relatively low (~ -25%), which may be attributed to specific processes at the high-altitude that are potentially not fully accurately resolved by SPHY. However, having discharge accurately resolved at lower stations is more important for the hydrological representation of the entire catchment.

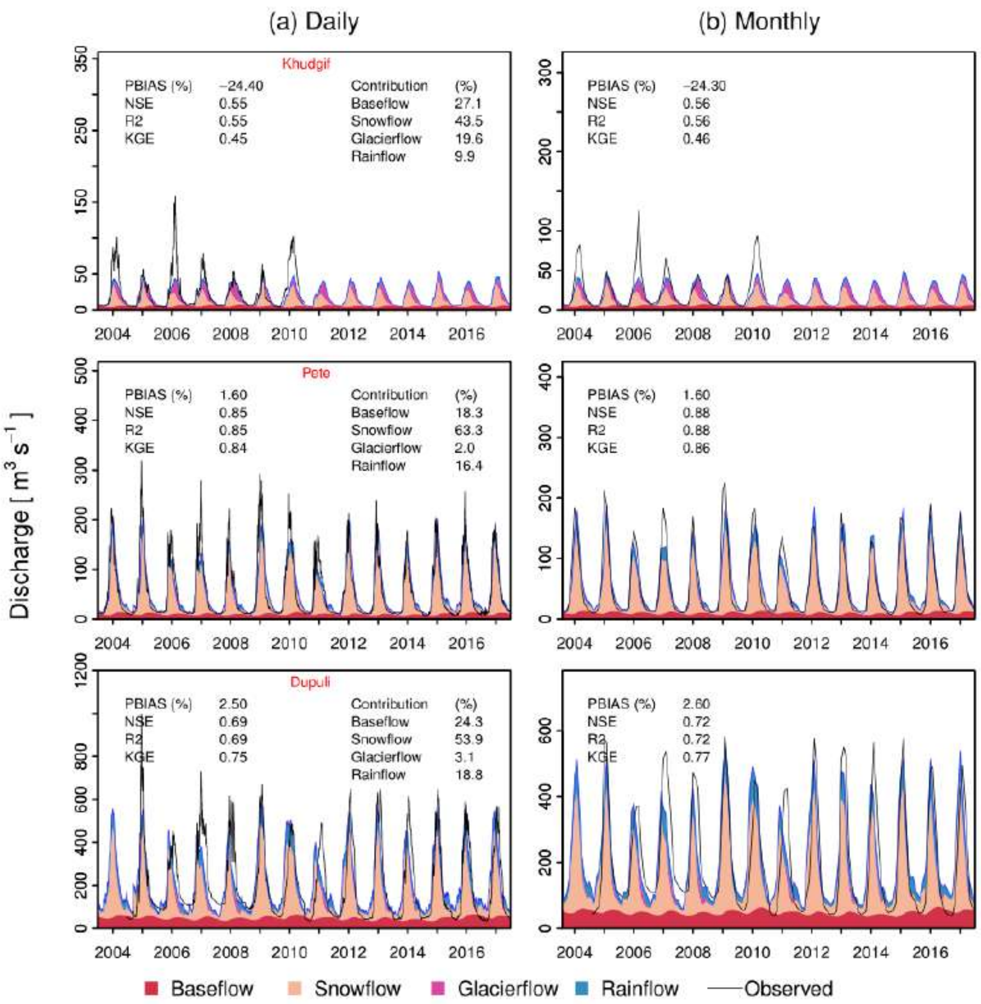

Figure 60. Observed and simulated discharge with the distinction of flow components (baseflow, snow, glacier, and rain runoff) at three calibration and validation stations/hydroposts locations, Khudgif, Pete and Dupuli for 2004-2017). The top left part of the figure shows values for model performance indicators; percent bias (PBIAS), Nash-Sutcliffe efficiency criterion (NSE), coefficient of determination (R2) and Kling-Gupta Efficiency (KGE) at the top left corner. The top right part of the figure shows the contribution of stream flow contributors to the total flow (expressed in %).

A2.2 Water Allocation Modelling using WEAP

WEAP («Water Evaluation And Planning» system) is a user-friendly software tool that takes an integrated approach to water resources planning. (Figure 61).

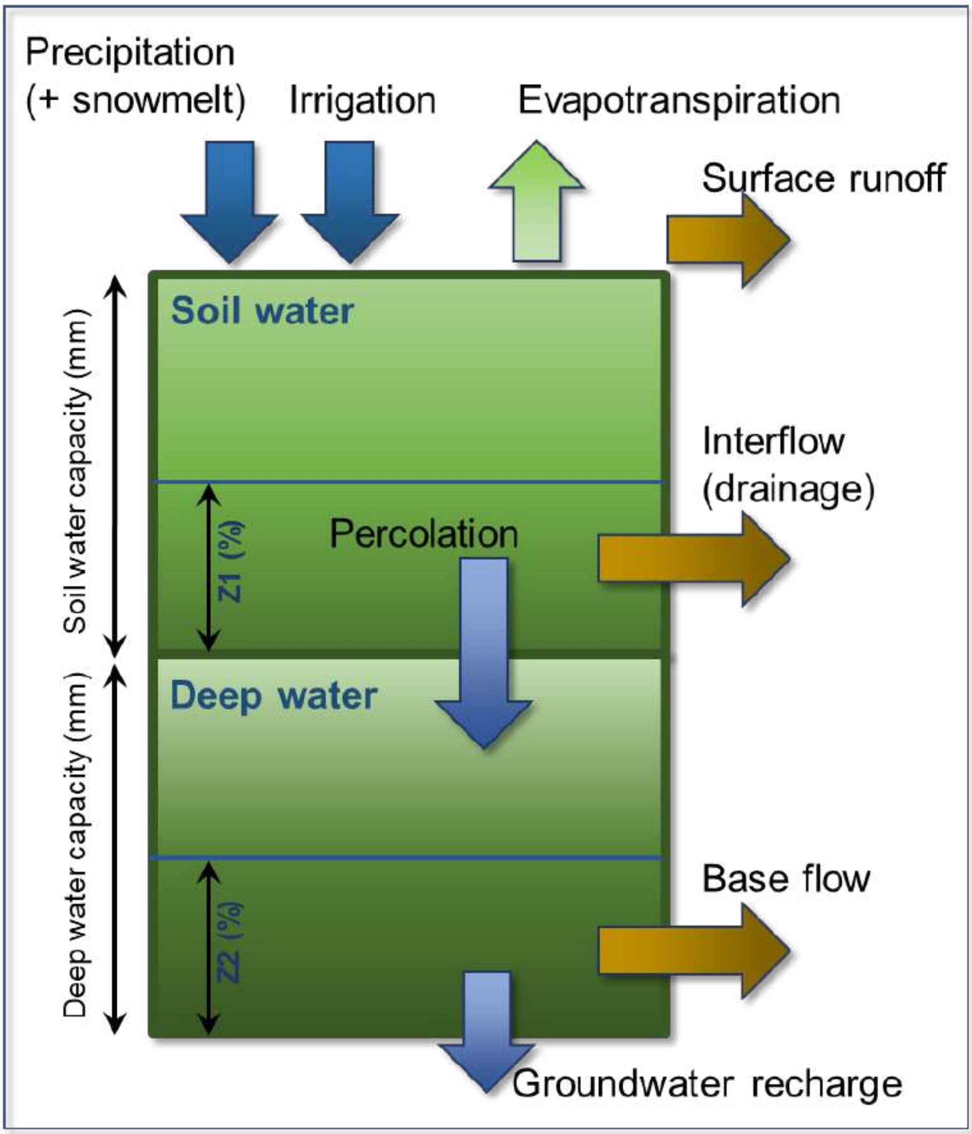

Figure 61. Processes included in the WEAP module are calculated at the calculation unit-level.

Availability and access to good quality data is essential for water allocation analysis using WEAP. Linkages with the SPHY model and focusing on relative differences (comparing base scenario with intervention scenarios) is the best strategy to tackle data quality issues. Required input data can be divided into the following main categories:

- Model building:
    - Static data[18]
        - Digital Elevation Models
        - Soils
        - Land use, land cover

18 Nota that static data can still vary over longer time frames, but are fairly constant over days/weeks

        - Population
        - Reservoir operational rules
        - Allocation (priority) rules
    - Dynamic data
        - Climate (rainfall, temperature, windspeed, relative humidity)
        - Evapotranspiration by crops and natural vegetation
        - Water demands by all sectors
- Model validation/calibration
    - Stream flow
    - Reservoir releases
    - Hydropower generation

A typical example of the flexibility and scalability of the WEAP model to deal with data is that water demands can be included as a total amount of water, but can be also estimated by WEAP using population, their daily required intake and daily and/or monthly variation. Similarly, climate data can be entered at annual, monthly, 10-days or daily level.

The more refined the input dataset is, the higher the reliable of the WEAP model scenarios will be. In the result section the reliability of the model will be demonstrated by comparing observed and simulated flows.

This feature is very useful in areas with low data availability or where more and better-quality data will become gradually available as the project progresses. The WEAP set-up gives the user the flexibility to add more detailed data when it becomes available, without having to start from scratch with every updated data set. This approach is a clear benefit for using the SPHY-WEAP model chain at this moment in Tajikistan, because it fits perfectly the Tajik context characterized by low data availability and gradual improved data collection with the assistance of development partners. Nevertheless, this only works if local stakeholders share the data.

Sources of data can be various. Some input data will need to be locally sourced as those are not available in the public domain or are hard to detect from satellite (Figure 10). Other relevant input data for WEAP can originate from quickly accessible global data sources. In general, a WEAP model can be developed for any location on earth using quickly accessible data sources. Depending on the question and the detail required additional local data will increase the reliability of the results.

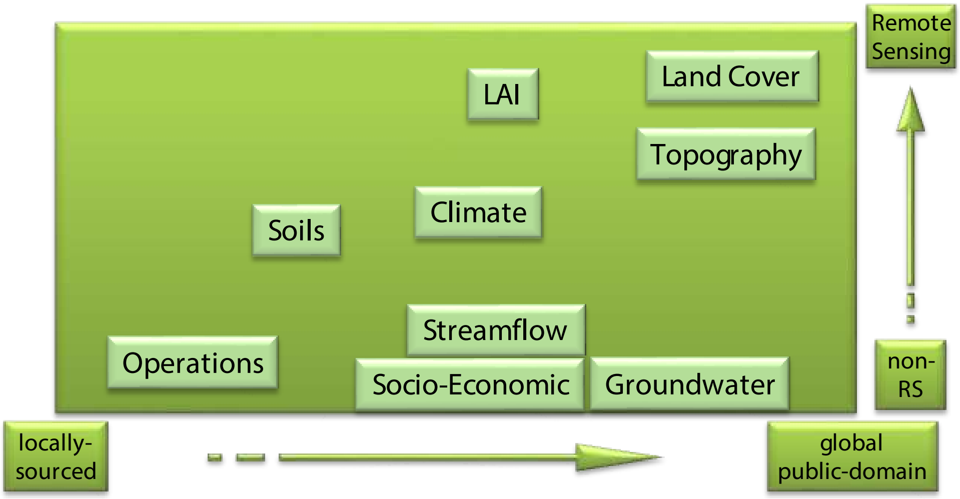

Figure 62: Development in data availability to support water allocation tools over the last 20 years.

A2.2.1 Data sets

Jamoat

The jamoats («village communes») are the third-level administrative divisions in Tajikistan. As of January 2020, there are 368 rural jamoats, 65 towns and 18 cities in Tajikistan. Each jamoat is further subdivided into villages (or deha or qyshqol). The Zarafshon area has 25 jamoats, which are shown in Figure 63.

Strategic water allocation analysis requires a more aggregated approach and, therefore, those 25 Jamoats have been aggregated into 9 Water Allocation Units (Figure 64). Note that those water allocation units are completely aligned with prior watershed divisions of the MEWR but at a higher aggregation level. Some of the key characteristics of those Water Allocation Units is shown in Table 23.

Note that specific data per Jamoats can be obtained also from the JAMBI[19] (Jamoat-level Basic Indicators) dataset.

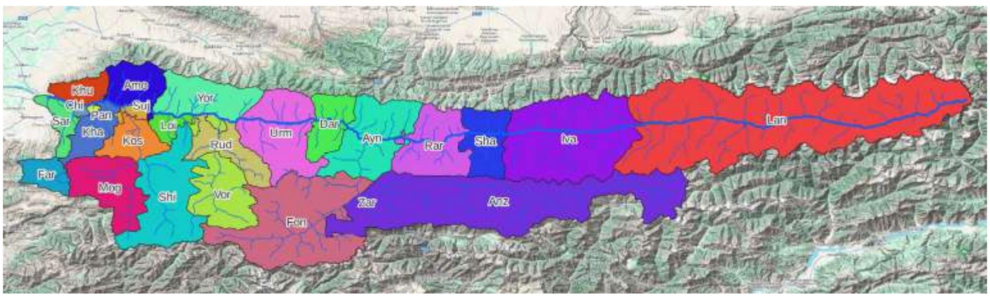

Figure 63. The 25 Jamoats in the Zarafshon River Basin.

19 https://untj.org/jambi-project

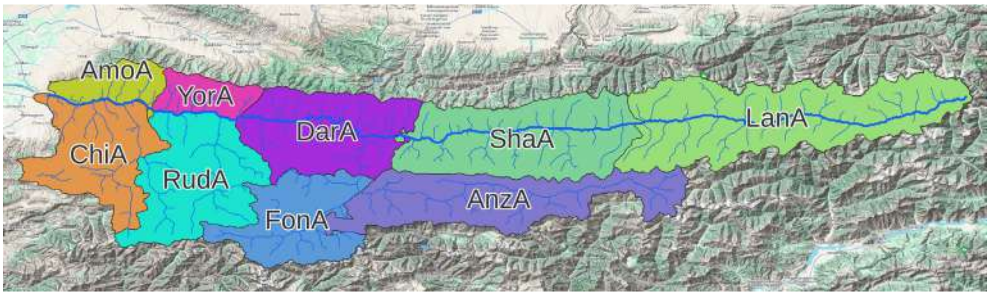

Figure 64. The aggregated Jamoats into nine Water Allocation Units

Table 22. Final calibrated model parameters with description, units, and values for ZRB-SPHY model.

Tajik	Latin	Generic	Abbr	WA-units
Айнӣ	Ajnӣ	Ayni	Ayn	DarA
Амондара	Amondara	Amondara	Amo	AmoA
Анзоб	Anzob	Anzob	Anz	AnzA
Вору	Voru	Voru	Vor	RudA
Дар-Дар	Dar-Dar	Dar-Dar	Dar	DarA
Ёри	Ëri	Yory	Yor	YorA
Зарафшон	Zarafšon	Zarafshan	Zar	AnzA
Иван Тоҷик	Ivan Toҷik	Ivan Tojik	Iva	ShaA
Косатарош	Kosataroš	Kosatarosh	Kos	ChiA
Лангар	Langar	Langar	Lan	LanA
Лоиќ Шералӣ	Loiќ Šeralӣ	Loik Sherali	Loi	RudA
Моѓиён	Moѓiën	Mogiyon	Mog	ChiA
Панҷакент	Panҷakent	Panjakent	Pan	ChiA
Рарз	Rarz	Rarz	Rar	ShaA
Рӯдакӣ	Rӯdakӣ	Rudaki	Rud	RudA
Саразм	Sarazm	Sarazm	Sar	ChiA
Сӯҷина	Sӯҷina	Sujina	Suj	ChiA
Урметан	Urmetan	Urmetan	Urm	DarA
Фароб	Farob	Farob	Far	ChiA
Фондарё	Fondarë	Fondaryo	Fon	FonA
Халифа Ҳасан	Halifa Ҳasan	Khalifa Hasan	Kha	ChiA
Хурмӣ	Hurmӣ	Khurmi	Khu	AmoA
Чинор	Činor	Chinor	Chi	ChiA
Шамтуч	Šamtuč	Shamtuch	Sha	ShaA
Шинг	Šing	Shing	Shi	RudA

A2.2.2 WEAP Water Allocation Model

The WEAP model was setup using the 9 aggregated Jamoats as presented above. For each of those 9 Jamoats four demand sites and three supply sides were considered. The four demand types were for Domestic (Dom), Industry (Ind), Irrigation (Irr) and Livestock (Liv)[20]. The supply side was split into Snow, Rain and Glacial (Glac) which is converted by SPHY in baseflow and runoff

Water supply data was provided by the SPHY basin scale model for each of the 9 Jamoats. Data were provided in millimeters per month for the three components (rain, snowmelt, glacial melt).

For the four demand types, data were provided for the 25 Jamoats in the Zarafshon basin. Those were aggregated to the 9 Jamoats used in the WEAP model.

The model was setup for three time periods relevant for planning purposes. That 20-year period was selected to ensure that climate as well as weather variation (year-to-year) are captured.

- Reference period: 2001–2020
- Near future: 2031–2050
- Distant future: 2061-2080

The entire model was setup to run on a monthly base. To consider year-to-year and monthly variation. it was assumed that the weather patterns (monthly variation) for the future are based on the reference period. So, for example if Mar-2001 was relatively dry, also Mar-2031 and Mar-2061 were relatively dry. Obviously, climate (the long-term temperature and precipitation) is not the same during those future periods. This approach is straightforward; to ensure better long-term planning and strategy a more rigorous climate change analysis is needed.

The entire setup of the WEAP model is shown in Figure 66 and Figure 67, while the linkages of SPHY and WEAP is schematically shown in Figure 65

20 In the WEAP model also one letter abbreviations were used: Domestic (Dom, D), Industry (Ind, M (from manufacturing)), Irrigation (Irr, I) and Livestock (Liv, L).

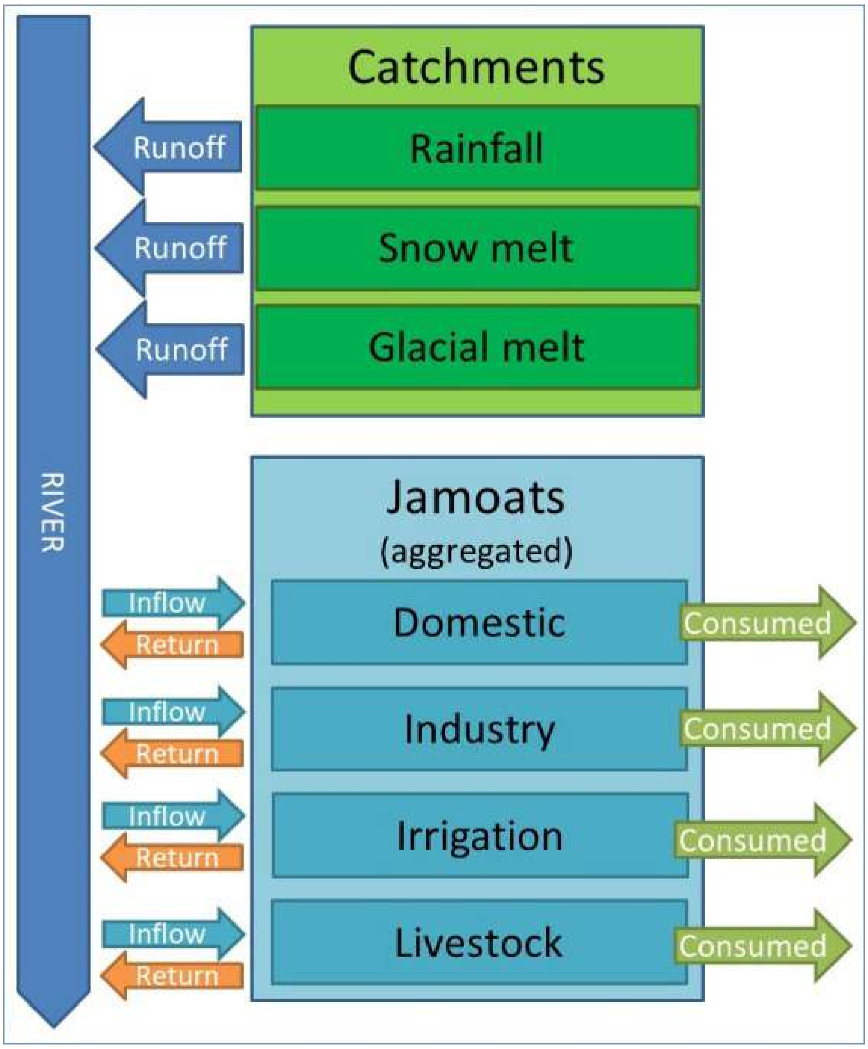

Figure 65. Schematic representation of one aggregated Jamoat water resources flows as setup in the WEAP model. Note that “runoff” includes baseflow as well as fast runoff.

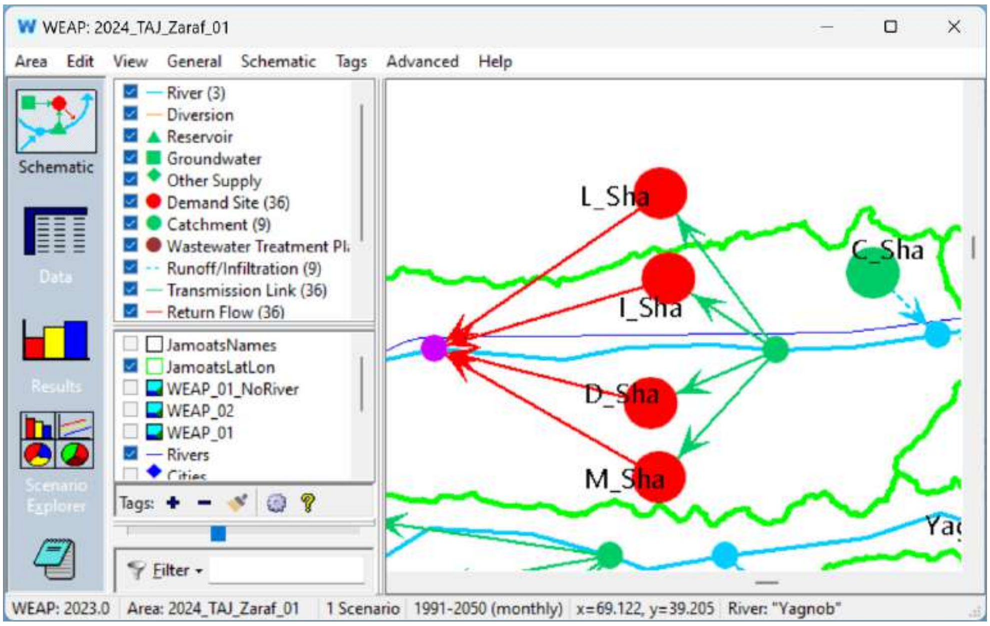

Figure 66. Screenshot of WEAP zoomed in on one aggregated Jamoat.

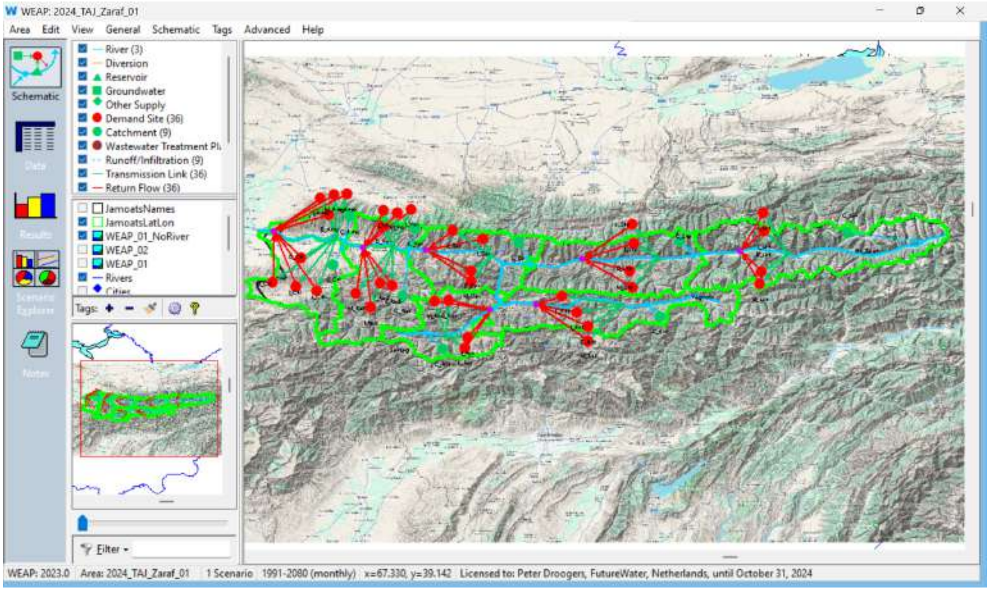

Figure 67. Screenshot of the schematic layout of Zarafshon as modeled using WEAP

A2.2.3 Inflow data from SPHY using Cycle

The WEAP water allocation model uses flow data as generated by the SPHY model. The reference period is 1991-2020. In order to use those data for the future an adjustment factor on those baseline data is used.

With "Cycle" where the two years reflect the starting and end year to be used for the future. In this study a period of 30 years (1991-2020) was used for each year after 2020. i.e. 2021 will use same climate as 1991.

ReadFromFile(Data\SupplySPHY.csv, «AmoA», , , , , ,1991 ,2020 , Cycle)

Note that if Cycle is provided without StartYear and EndYear, WEAP takes the entire range as provided in the dataset. For this study the following line will provide the same result.

ReadFromFile(Data\SupplySPHY.csv, «AmoA», , , , , , , , Cycle)

The year 1991 is used for 2021, 2051, 2081. Therefore, the three time periods of 20 years to consider are:

- 2001 – 2021
- 2031 – 2050
- 2061 – 2080

A2.3 Relevance of using SPHY and WEAP

Selection of the most appropriate model for this specific project is an important decision to be taken. **Note that the Ministry of Energy and Water Resources is responsible for water allocation in Tajikistan.**

To improve the water allocation capacities of the Ministry of Energy and Water Resources to accomplish the objectives of the Water Sector Reform Program in Tajikistan the SPHY and WEAP models have been selected.

In the next section, we present the relevance of these two models and the integrated approach aligned with the needs of the Ministry of Energy and Water Resources and other stakeholders in Tajikistan.

A2.3.1 Why SPHY?

SPHY is primarily designed to address processes in high mountain regions, with a strong focus on the cryosphere. It has been applied in various contexts and mountain regions worldwide, proving effective in similar environments. The choice of model depends on the specific project and the required analysis. Key areas of SPHY's application include past and future hydrological changes, basin management, irrigation management, land degradation and restoration, energy, hydroclimatic extremes, and compound events, among others.

There is no best model available which is adequate for all types of applications. The choice of model is driven by the overall objective of the project. However, SPHY stands out as compared to other models due to its wide range of functionalities such as:

Free

The SPHY model is free software available on GitHub, allowing anyone to use, redistribute, and modify it under the terms of the GNU General Public License. It includes a comprehensive database of projects focused on mountainous regions. The software also offers a well-organized database, along with clear tutorials and training materials to support users.

Spatial scale

SPHY model can be applied to flexible ranges of spatial scales such as small-scale farm, medium scale sub-catchment and catchment, and large scale regional and global applications. SPHY helps the user to better understand the spatial differences and variability of the key hydrological process. Further, the model can be run on different spatial scales for different processes within the same simulation. For instance, the glacier can be run on 50 meters resolution while the model resolution is 1000 meters.

Temporal scale

SPHY model can be applied from sub-daily to daily, weekly, monthly and yearly time steps depending on the daily variations of the key hydrological processes and data availability.

Adaptability

SPHY model can be easily adapted for the use in different climatic conditions around the world. This is very useful if the user is studying hydrological processes in regions where not all hydrological processes are relevant. A user may for example be interested in studying irrigation water requirements in central Africa. For this region glacier and snow melting processes are irrelevant and can thus be switched off. Another user may only be interested in simulating moisture conditions in the first soil layer, allowing the possibility to switch off the routing and groundwater modules.

Less data requirement

The model can be supplied with data on a parsimonious and data hungry approach depending on the data availability in the region. A user can use any of ground-based observations such as hydrological data: discharge, cryospheric data: snow cover, glacier mass balance, crop data: crop coefficients static, leaf area index, lake and reservoir information etc., if available to better represent and improve the accuracy of the model.

User friendliness

SPHY model is user-friendly and can be applied by anyone having a general knowledge on key hydrological processes. A static constant or stochastic time series or a more complex raster maps can be provided as inputs to the model as specified by the user. Further, SPHY model provides a wealth of output data that can be selected based on the preference of the user. **Spatial output can be presented as spatial maps of all the hydrological processes.** These maps can be generated on daily base, but also the aggregates at monthly or annual time periods. Time-series can be generated for each location in the study area as specified by the user.

A2.3.2 Why WEAP?

There is not a single valid model fitting every purpose (Beven, 2001, 2004). The selection of a model depends on the specific objectives of a study, which may include addressing issues such as the following: droughts, floods, allocation, crops, complexity, scalability and scenarios.

Figure 68 provides a brief qualitative assessment of the capabilities of the different models in simulating the wide range of objectives. The aim of the IRDP/TRIGGER Project intervention is to improve the capacities of the Ministry of Energy and Water Resources (MEWR) in terms of water allocation by undertaking scenario analysis. For water allocation and scenario analysis, the WEAP model stands out (Figure 68). Since the complexity of the WEAP model, given its nice interface, is also relatively low, the model can also be used for training.

	Drought	Floods	Allocation	Crops	Complexity	Scalable	Scenarios
HEC-HMS	2	3	1	1	3	3	3
HEC-RAS	1	5	2	1	4	2	2
SPHY	3	4	2	2	2	4	4
WEAP	5	4	5	5	1	5	5
SWAT	4	3	3	3	2	4	3
SOURCE	4	4	4	2	4	5	4
SWMM	2	5	2	1	2	3	2
SOBEK	1	5	2	2	3	2	2
MIKE BASIN	4	3	4	2	2	4	4
MIKE SHE	3	3	3	3	5	2	1

Figure 68. Qualitative (expert based) assessment of some catchment scale models that might be used for the project. Scores 1 (=limited) to 5 (=well suited). Note that the color scale for "Complexity" is reversed to maintain green for "better" and red for "worse."

Some other strengths of WEAP not covered by those seven criteria yet important for the project are the following:

- WEAP is used in over 180 countries and has many active users in India.
- WEAP can be automated and coupled with other models. Coupling with SPHY (also used in the project) has been successfully done in many other projects.
- WEAP has excellent (and free) training modules.
- WEAP is tailored towards starting in an explorative way and gradually including other components for more detailed analysis.
- WEAP is the de-facto standard for many developing and funding agencies to make investment decisions.
- WEAP is freely available

As presented above, there are various reasons for choosing the WEAP framework as the most relevant water allocation model to achieve this. Most important is that **WEAP is completely focused on scenario analysis in a user-friendly approach. Second, WEAP is very scalable, and a first-order setup of a particular region can be easily expanded when more data/ resources are available.** Third, WEAP is commonly used world-wide for IWRM (Integrated Water Resources Management) analyses. Finally, WEAP is freely available for organizations in developing countries.

A detailed discussion on WEAP can be found in the WEAP manual which can be freely downloaded from the WEAP website (http://www.weap21.org/).

A2.3.3 The SPHY-WEAP approach and relevance with local context

SPHY-WEAP coupling provides a comprehensive approach to water resources planning and assessing socio-economic and climate change impacts, offering the following features:

Integrated Approach

Unique approach for conducting integrated water resources planning and impact assessments of socio economic and climate changes. The results of the SPHY-WEAP model were used to support the process of formulation of the ZRBMP which describes and proposes how the ZRB should develop in 5-year cycles.

Stakeholder Process

Transparent structure facilitates engagement of diverse stakeholders in an open process. The results of the SPHY-WEAP model were communicated by the Zarafshon RBO to the River Basin Council members of the ZRB to facilitate the understanding of water availability and use in Zarafshon river basin.

Water Balance

A database maintains water demand and supply information to drive mass balance model on a link-node architecture that can be coupled with the National Water Information System.

Simulation Based

Calculates water demand, supply, runoff, flooding, infiltration, overall crop water requirements, flows, storage, pollution generation, treatment, discharge and in-stream water quality under varying hydrologic and policy scenarios. The model can be used at any time by the MEWR to simulate water supply and demand scenarios accordingly to account for new data entered in the NWIS or simulate river basin scenarios according to potential policy developments to support future decision-making.

Hydrological Processes

Semi-distributed three-layer bucket approach (soil water, deep water, groundwater). This can be helpful in better understanding how a system works which will support better decision making.

Policy Scenarios

Evaluates a full range of water development and management options and takes account of multiple and competing uses of water systems. This can be from national down to local water allocation scenarios.

User-friendly Interface

Graphical drag-and-drop GIS-based interface with flexible model output as maps, charts and tables. A selected team of young water and climate specialists were trained in the use of the SPHY and WEAP model chain. The easy-to-use features of both softwares, such as, maps charts, tables allows the Ministry of Energy and Water Resources, CGR and IWP to count now with a team that can model water supply and demand in the ZRB at any time.

Model Integration

Links to other models and software, such as SPHY, SWAT, QUAL2K, MODFLOW, MODPATH, PEST, Excel, HEC-RAS and GAMS, is possible.

ANNEX 3: METEOROLOGICAL STATIONS INSTALLATION IN THE ZRB IN TAJIKISTAN

To improve the calibration and validation of the SPHY-WEAP model developed under the IRDP/TRIGGER Project, the IRDP/TRIGGER Project coordinated with CARITAS Switzerland the installation of a limited number of low-cost weather stations in selected locations of the Zarafshon River Basin. **At the moment of finalization of this report, it was reported that at least 10 low-cost weather stations have been installed in Zarafshon River Basin, out of the 46 locations proposed by the IRDP/TRIGGER Project, as shown in Table 24 at the end of this Annex 3.**

To determine and propose potential locations for the low-cost weather stations in the ZRB, a **GIS analysis** was conducted by the IRDP/TRIGGER Project. This analysis is further explained in detail below supported by Figures 69 through 74. In addition to the GIZ analysis, **additional factors were considered to select the optimal locations for the installation of the weather stations** such as, internet coverage of at least 2G, safe location from potential vandalism, possibility to install a fence around the weather station and if possible, within the farmland of a potential responsible farmer.

The plan for the installation of the low-cost weather stations in Tajikistan was always coordinated with the **Agency of Meteorology of Tajikistan**, as the owner of such weather stations. The installation process was a joint effort by the Zarafshon RBO, t**he respective heads of the Jamoats and different representatives of the communities at sub-catchment level, including relevant farmers.**

Figure 69 below shows the existing limited sensor network in Zarafshon River Basin.

Figure 69. ZRB with existing sensor network (yellow dots). Red outlined regions indicate Water Management Areas (WMA) and purple regions indicate Water Objects (WOL). The color gradient (dark brown shade being the high and green shade being the low elevation) in the background indicates elevation.

The planned low-cost weather stations should be able to measure meteorological variables such as precipitation, temperature, relative humidity, etc. to improve model calibration and validation of the SPHY-WEAP model developed under the IRDP/TRIGGER Project. The weather stations should capture the wide range of climatic variables within the river basin, spatial variation in rainfall in numerous valleys, and vertical gradients in temperature that are important for snow and glacier melt. The steps for determining the potential locations are based on the following steps:

1. Identification of major tributaries that contribute to streamflow
2. Exclusion of areas above the maximum elevation (3500m) of sensor placement
3. Even horizontal distribution placement
4. Inclusion of vertical transects near major tributaries and glaciers
5. Exclusion of site characteristics that hinder accessibility
6. Road buffer analysis for location accessibility
7. Spatial analysis for GSM network availability

The glaciers and snowmelt contribute to about 50-60% of the streamflow in the ZRB. So, the analysis should not neglect these processes. At the same time, topography also drastically impacts the distribution of rainfall and temperature. The weather station network should be able to capture these spatial and elevation-dependent variations. Using a Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM), sub-catchments were delineated with a Strahler stream order of 7 (Figure 70).

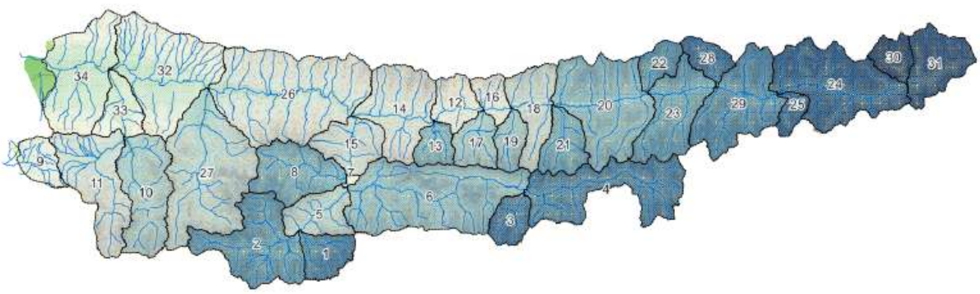

Figure 70. Sub-catchments in the ZRB in Tajikistan based on Strahler stream order number 7. The numbers indicate the sub-catchment number, the darkness of the blue color indicates its snow persistence, and thus indicates the importance of the sub-catchment to snow and glacier melt contributions to the river.

The weather stations are built to measure the liquid part of precipitation and are not reliable for measuring the snow as they tend to clog. Therefore, the sensors can only be placed up to an elevation of 3500 m AMSL (Figure 71). Areas above this threshold were excluded from the analysis.

Figure 71. ZRB in Tajikistan with sub-basin delineation. The white areas indicate elevations above 3500 m AMSL and are excluded in the analysis. The color gradient (white color represents elevation above 3500 m AMSL) in the background indicates elevation.

Using MODIS snow cover data, the snow persistence (% of the time a particular snow pixel was covered with snow) was calculated between 2004 and 2023. Combining the MODIS snow persistence with the sub-catchments the more important tributaries to streamflow were identified. Although most sub-catchments are likely to receive a meteorological station, the sub-catchments with a high snow persistence (glaciers have 100%) are prioritized and receive a higher density of sensor placement. The resulting map shows that especially the eastern and most southern sub-catchments have a high snow persistence and are most of the time covered by snow and/or glaciers (Figure 70). These regions will therefore be prioritised in sensor placement, and also a higher density of sensor placement will occur.

In valleys, sensors are placed evenly with an approximate distance of around 25 km. The aspect or the direction of the slope, is considered. In priority sub-catchments, areas with high snow and glacier coverage, vertical transects of 3 or more weather stations are preferred (Figure 72).

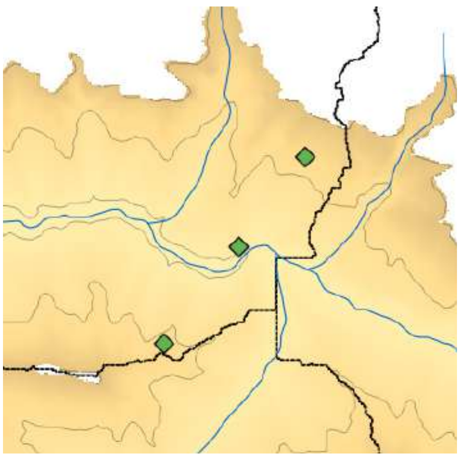

Figure 72. Transect of low-cost weather stations near glaciers.

In terms of horizontal placement, in valleys, a sensor is placed each 25 km along the Zarafshon River Basin, also within each sub-catchment. It is preferable that the locations of the sensors are placed within a radius of about 2 km from the road network (Figure 73). Using OpenStreetMap a road network was extracted. A buffer of 2 km on both sides of the road was created to find areas that are accessible by road and a short hike. The areas between the red lines are within 2 km of the nearest known road. The weather stations should be placed within these boundaries. The map below shows the areas excluded in sensor placement in white. Other land uses that are not preferable for sensor placement, such as forests and built-up areas were also excluded.

Figure 73. ZRB where red lines indicate 2-km buffers around the existing road network. The area in between the red lines is accessible by car. The color gradient in the background indicates elevation.

The final result of this GIS spatial analysis is shown in the map below (Figure 74). The proposed 46-point locations should be interpreted as potential locations. Exact conditions should always be assessed on the ground, and sensors can always be placed within a 500 m range of the selected locations

Figure 74. Distribution of potential sensor placement and sensor number in the Zarafshon River Basin. Red outlined regions indicate Water Management Areas (WMA) and purple regions indicate Water Objects (WOL). The colour gradient in the background displays elevation.

The potential sensor placement area properties are listed in Table 24 and in orange are the prioritized locations for the installation of 10 weather stations out of the 46 proposed ones.

Table 24. Potential sensor placement location properties and prioritized locations highlighted in orange.

Sensor nr.	Sub-basin	Water Management Area	Water Objects	Elevation [m]	Aspect [°]	Longitude [°]	Latitude [°]
1	6	ВХУ «Зеравшан Верхний	река Фондарья	2596	158	69.132	39.192
2	6	ВХУ "Зеравшан Верхний"	река Фондарья	3145	188	69.147	39.207
3	24	ВХУ "Зеравшан Верхний"	река Матча	2701	163	70.336	39.429
4	24	ВХУ "Зеравшан Верхний"	река Матча	3526	209	70.334	39.44
5	24	ВХУ "Зеравшан Верхний"	река Матча	3053	338	70.34	39.415
6	6	ВХУ "Зеравшан Верхний"	река Фондарья	3119	47	69.116	39.175

7	17	ВХУ "Зеравшан Верхний"	река Матча	1983	104	68.981	39.343
8	12	ВХУ "Зеравшан Верхний"	река Матча	2903	54	68.915	39.456
9	18	ВХУ "Зеравшан Верхний"	река Матча	1941	2	69.148	39.413
10	19	ВХУ "Зеравшан Верхний"	река Матча	2857	14	69.073	39.328
11	18	ВХУ "Зеравшан Верхний"	река Матча	2975	127	69.099	39.467
12	18	ВХУ "Зеравшан Верхний"	река Матча	2889	272	69.202	39.346
13	20	ВХУ "Зеравшан Верхний"	река Матча	2610	253	69.285	39.484
14	21	ВХУ "Зеравшан Верхний"	река Матча	2695	118	69.28	39.307
15	20	ВХУ "Зеравшан Верхний"	река Матча	2408	196	69.496	39.439
16	29	ВХУ "Зеравшан Верхний"	река Матча	3068	5	69.836	39.435
17	24	ВХУ "Зеравшан Верхний"	река Матча	2512	192	70.123	39.466
18	6	ВХУ "Зеравшан Верхний"	река Фондарья	2896	290	68.879	39.121
19	6	ВХУ "Зеравшан Верхний"	река Фондарья	3153	1	68.685	39.101
20	6	ВХУ "Зеравшан Верхний"	река Фондарья	2207	82	68.573	39.15
21	6	ВХУ "Зеравшан Верхний"	река Фондарья	2709	39	68.936	39.21
22	2	ВХУ "Зеравшан Верхний"	река Фондарья	2976	62	68.268	39.082
23	2	ВХУ "Зеравшан Верхний"	река Фондарья	3698	228	68.266	39.159
24	7	ВХУ "Зеравшан Верхний"	река Фондарья	2320	277	68.547	39.216
25	8	ВХУ "Зеравшан Верхний"	река Фондарья	2094	297	68.432	39.233
26	8	ВХУ "Зеравшан Верхний"	река Фондарья	2492	189	68.354	39.249
27	8	ВХУ "Зеравшан Верхний"	река Фондарья	2688	329	68.267	39.246
28	15	ВХУ "Зеравшан Верхний"	река Фондарья	2473	122	68.465	39.318
29	15	ВХУ "Зеравшан Верхний"	река Фондарья	3498	58	68.632	39.286

30	27	ВХУ "Зеравшан Нижний"	река Киштут	2403	136	67.971	39.237
31	27	ВХУ "Зеравшан Нижний"	река Киштут	2520	23	68.118	39.275
32	27	ВХУ "Зеравшан Нижний"	река Киштут	1569	278	68.055	39.381
33	14	ВХУ "Зеравшан Верхний"	река Матча	1746	352	68.579	39.379
34	26	ВХУ "Зеравшан Верхний"	река Зеравшан Верхний	3160	225	68.567	39.501
35	26	ВХУ "Зеравшан Верхний"	река Зеравшан Верхний	1424	22	68.254	39.433
36	34	ВХУ "Зеравшан Нижний"	река Зеравшан Нижний	1073	184	67.716	39.513
37	11	ВХУ "Зеравшан Нижний"	река Магиян	1624	346	67.66	39.237
38	33	ВХУ "Зеравшан Нижний"	река Магиян	1507	34	67.788	39.337
39	10	ВХУ «Зеравшан	река Магиян	2889	124	67.86	39.156
40	2	ВХУ "Зеравшан Верхний"	река Фондарья	3204	71	68.315	39.039
41	5	ВХУ "Зеравшан Верхний"	река Фондарья	2244	235	68.426	39.116
42	32	ВХУ "Зеравшан Нижний"	река Киштут	1212	198	68.079	39.456
43	6	ВХУ "Зеравшан Верхний"	река Фондарья	2696	209	68.726	39.194
44	12	ВХУ "Зеравшан Верхний"	река Матча	1828	177	68.822	39.383
45	32	ВХУ "Зеравшан Нижний"	река Зеравшан Нижний	1158	327	67.924	39.455
46	34	ВХУ "Зеравшан Нижний"	река Зеравшан Нижний	917	11	67.478	39.51

REFERENCES

Aalstad, K., Westermann, S., Schuler, T. V., Boike, J. and Bertino, L.: Ensemble-based assimilation of fractional snow-covered area satellite retrievals to estimate the snow distribution at Arctic sites, Cryosphere, 12(1), 247–270, doi:10.5194/TC-12-247-2018, 2018.

Aalto, J., Kämäräinen, M., Shodmonov, M., Rajabov, N. and Venäläinen, A.: Features of Tajikistan's past and future climate, Int. J. Climatol., 37(14), 4949–4961, doi:10.1002/joc.5135, 2017.

Azam, M. F., Kargel, J. S., Shea, J. M., Nepal, S., Haritashya, U. K., Srivastava, S., Maussion, F., Qazi, N., Chevallier, P., Dimri, A. P., Kulkarni, A. V., Cogley, J. G. and Bahuguna, I.: Glaciohydrology of the Himalaya-Karakoram, Science (80-.)., 373(6557), doi:10.1126/SCIENCE.ABF3668/ASSET/7E3B4E6D-4A64-4A36-9CC5-24AF20033A89/ASSETS/IMAGES/LARGE/SCIENCE.ABF3668-FA.JPG, 2021.

Bárdossy, A.: Calibration of hydrological model parameters for ungauged catchments, Hydrol. Earth Syst. Sci., 11(2), 703–710, doi:10.5194/hess-11-703-2007, 2007.

Beven, K.: How far can we go in distributed hydrological modelling?, Hydrol. Earth Syst. Sci., 5(1), 1–12, doi:10.5194/hess-5-1-2001, 2001.

Beven, K.: Robert E. Horton's perceptual model of infiltration processes, Hydrol. Process., 18(17), 3447–3460, doi:10.1002/hyp.5740, 2004.

Bisset, R. R., Dehecq, A., Goldberg, D. N., Huss, M., Bingham, R. G. and Gourmelen, N.: Reversed Surface-Mass-Balance Gradients on Himalayan Debris-Covered Glaciers Inferred from Remote Sensing, Remote Sens. 2020, Vol. 12, Page 1563, 12(10), 1563, doi:10.3390/RS12101563, 2020.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M.: The state and fate of himalayan glaciers, Science (80-.)., 336(6079), 310–314, doi:10.1126/science.1215828, 2012.

Cucchi, M., Weedon, G., Amici, A., Bellouin, N., Lange, S., Schmied, H. M., Hersbach, H. and Buontempo, C.: WFDE5: bias adjusted ERA5 reanalysis data for impact studies, Earth Syst. Sci. Data Discuss., (April), 1–32, doi:10.5194/essd-2020-28, 2020.

Eekhout, J. P. C., Terink, W. and De Vente, J.: Assessing the large-scale impacts of environmental change using a coupled hydrology and soil erosion model, Earth Surf. Dyn., 6(3), 687–703, doi:10.5194/esurf-6-687-2018, 2018.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D.: The Shuttle Radar Topography Mission, Rev. Geophys., 45(2), doi:10.1029/2005RG000183, 2007.

Fiddes, J. and Gruber, S.: TopoSCALE v.1.0: Downscaling gridded climate data in complex terrain, Geosci. Model Dev., 7(1), 387–405, doi:10.5194/gmd-7-387-2014, 2014.

Fiddes, J., Endrizzi, S. and Gruber, S.: Large-area land surface simulations in heterogeneous terrain driven by global data sets: Application to mountain permafrost, Cryosphere, 9(1), 411–426, doi:10.5194/TC-9-411-2015, 2015.

Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, A.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, Cryosphere, 7(4), 1263–1286, doi:10.5194/tc-7-1263-2013, 2013.

Geweke, J.: Efficient Simulation from the Multivariate Normal and Student-t Distributions Subject to Linear Constraints and the Evaluation of Constraint Probabilities, Comput. Sci. Stat., 23, 1998.

Groll, M., Opp, C., Kulmatov, R., Ikramova, M. and Normatov, I.: Water quality, potential conflicts and solutions—an upstream–downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan), Environ. Earth Sci., 73(2), 743–763, doi:10.1007/s12665-013-2988-5, 2013.

Gupta, H. V., Kling, H., Yilmaz, K. K. and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, J. Hydrol., 377(1–2), 80–91, doi:10.1016/J.JHYDROL.2009.08.003, 2009.

Hall, D. K. and Riggs, G. A.: MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG Dataset Version 6, https://nsidc.org/data/MOD10CM, 2015.

Hargreaves, G. and Samani, Z.: Reference Crop Evapotranspiration from Temperature, Appl. Eng. Agric., 1(2), 96–99, doi:10.13031/2013.26773, 1985.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J. N.: The ERA5 global reanalysis, Q. J. R. Meteorol. Soc., 146(730), 1999–2049, doi:10.1002/qj.3803, 2020.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282(1–4), 104–115, doi:10.1016/S0022-1694(03)00257-9, 2003.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. and Baillie, J. E. M.: Importance and vulnerability of the world’s water towers, Nature, 577(7790), 364–369, doi:10.1038/s41586-019-1822-y, 2020.

Kang, S., Xu, Y., You, Q., Flügel, W. A., Pepin, N. and Yao, T.: Review of climate and cryospheric change in the Tibetan Plateau, Environ. Res. Lett., 5(1), doi:10.1088/1748-9326/5/1/015101, 2010.

Kargel, J. S., Leonard, G. J., Bishop, M. P., Kääb, A. and Raup, B. H.: Global land ice measurements from space, Springer., 2014.

Karssenberg, D., Schmitz, O., Salamon, P., Jong], K. [de and Bierkens, M. F. P.: A software framework for construction of process-based stochastic spatio-temporal models and data assimilation, Environ. Model. Softw., 25(4), 489–502, doi:https://doi.org/10.1016/j.envsoft.2009.10.004, 2010.

Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T. and Immerzeel, W. W.: Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at Seasonal to Decadal Time Scales, Water Resour. Res., 57(5), e2020WR029266, doi:10.1029/2020wr029266, 2021.

Khanal, S., Tiwari, S., Lutz, A. F., Hurk, B. V. D. and Immerzeel, W. W.: Historical Climate Trends over High Mountain Asia Derived from ERA5 Reanalysis Data, , 263–288, doi:10.1175/JAMC-D-21-0045.1, 2023.

Kirches, G., Brockmann, C., Boettcher, M., Peters, M., Bontemps, S., Lamarche, C., Schlerf, M., Santoro, M. and Defourny, P.: Land cover cci-product user guide-version 2, ESA Public Doc. CCI-LC-PUG, (2.4), 2014.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. and Immerzeel, W. W.: Impact of a 1.5 °C global temperature rise on Asia's glaciers, Nature, 549(7671), 257–260, doi:10.1038/nature23878, 2017a.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549, 257 [online] Available from: https://doi.org/10.1038/nature23878, 2017b.

Lange, S.: Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), Geosci. Model Dev. Discuss., 1–24, doi:10.5194/gmd-2019-36, 2019.

Lange, S.: ISIMIP3b bias-adjusted atmospheric climate input data (v1.1), ISIMIP Repos. [online] Available from: https://doi.org/10.48364/ISIMIP.842396.1 (ISIMIP Repository, 2021), 2021.

Liang, X., Lettenmaier, D. P., Wood, E. F. and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99(D7), 14415–14428, doi:10.1029/94jd00483, 1994.

Lu, H., Jia, J., Yin, Q., Xia, D., Gao, F., Liu, H., Fan, Y., Li, Z., Wang, X., Berger, A., Oimuhammadzoda, I. and Gadoev, M.: Atmospheric Dynamics Patterns in Southern Central Asia Since 800 ka Revealed by Loess-Paleosol Sequences in Tajikistan, Geophys. Res. Lett., 47(17), 1–10, doi:10.1029/2020GL088320, 2020.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P.: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, Nat. Clim. Chang., 4(7), 587–592, doi:10.1038/nclimate2237, 2014.

Merz, R. and Blöschl, G.: Regionalisation of catchment model parameters, J. Hydrol., 287(1–4), 95–123, doi:10.1016/j.jhydrol.2003.09.028, 2004.

Mishra, S.: Uncertainty and sensitivity analysis techniques for hydrologic modeling, J. Hydroinformatics, 11(3–4), 282–296, doi:10.2166/HYDRO.2009.048, 2009.

Nash, J. E. and Sutcliffe, J. V: River Flow Forecasting Through Conceptual Models Part I-a Discussion of Principles*, J. Hydrol., 10, 282–290, doi:10.1016/0022-1694(70)90255-6, 1970.

Normatov, P. I., Normatov, I. S., Normatov, P. I. and Normatov, I. S.: Monitoring of Meteorological, Hydrological Conditions and Water Quality of the Main Tributaries of the Transboundary Amu Darya River, Achiev. Challenges Integr. River Basin Manag., doi:10.5772/INTECHOPEN.74958, 2018.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., Yamkhin, J. and Zou, D.: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale, Earth-Science Rev., 193, 299–316, doi:10.1016/J.EARSCIREV.2019.04.023, 2019.

Obu, J., Westermann, S., Vieira, G., Abramov, A., Ruby Balks, M., Bartsch, A., Hrbáček, F., Kääb, A. and Ramos, M.: Pan-Antarctic map of near-surface permafrost temperatures at 1 km2 scale, Cryosphere, 14(2), 497–519, doi:10.5194/tc-14-497-2020, 2020.

Patil, S. and Stieglitz, M.: Modelling daily streamflow at ungauged catchments: What information is necessary?, Hydrol. Process., 28(3), 1159–1169, doi:10.1002/hyp.9660, 2014.

Pellicciotti, F., Buergi, C., Immerzeel, W. W., Konz, M. and Shrestha, A. B.: Challenges and uncertainties in hydrological modeling of remote hindu KushKarakoramHimalayan (HKH) Basins: Suggestions for calibration strategies, Mt. Res. Dev., 32(1), 39–50, doi:10.1659/MRD-JOURNAL-D-11-00092.1, 2012.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover, Nat. Geosci., 4(3), 156–159, doi:10.1038/ngeo1068, 2011.

Terink, W., Lutz, A. F., Simons, G. W. H., Immerzeel, W. W. and Droogers, P.: SPHY: Spatial Processes in Hydrology, Geosci. Model Dev. Discuss., 8(October), 1687–1748, doi:10.5194/gmdd-8-1687-2015, 2015.

UNEP: Environment and Security in the Amu Darya River Basin, 2011, Disasters, (September), 100 [online] Available from: https://www.grida.no/publications/202, 2011.

Vikhamar Schuler, T. and Østby, T. rn I.: Sval-Imp: A gridded forcing dataset for climate change impact research on Svalbard, Earth Syst. Sci. Data, 12(2), 875–885, doi:10.5194/ESSD-12-875-2020, 2020.

Wijngaard, R. R., Lutz, A. F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. B. and Immerzeel, W. W.: Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins, PLoS One, 12(12), 26, doi:10.1371/journal.pone.0190224, 2017.

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