# Current and future water balance of a mountain subcatchment of Issyk-Kul Lake, Tien Shan range, Kyrgyzstan

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*Mountain water balance, snow and glacier, surface runoff, future scenarios, distributed modeling,* Tien Shan.

## Abstract

Snow and ice dominated basins are particularly vulnerable to climate change but estimating their hydrological balance remains challenging in data-scarce regions like the Tien Shan mountains. With the overall aim of modeling of the large Issyk-Kul Lake basin in Kyrgyzstan, this article focuses on the hydrological balance of the Chon Kyzyl-Suu basin, a representative sub-catchment of the lake basin. The study involved two steps: first, calibration/validation of a distributed hydrological snow model, second, assessment of future trends in runoff, evaporation, snow melt and glacier melt under different climate scenarios. Our results show that the balance of the basin is already upset due to glacier mass loss and that groundwater processes play a significant role in generating discharge. Climate projections for the next 40 years (2020-2060) show no significant trend in

precipitation under scenario ssp2-4.5 but an 8.9% decrease in precipitation under scenario ssp5-8.5. at the same time, air temperature will increase by 0.4°C under scenario ssp2-4.5, and by 1.8°C under scenario ssp5-8.5. Under the "business as usual" scenario (ssp2-4.5), the annual river flow of the headwater basins should increase by 13%, or under the "pessimistic" ssp5-8.5 scenario, by 28%, mainly due to the increase in glacier runoff. These results make it possible to envisage realistic modeling at the scale of the lake at a daily time step.

# 1. Introduction

High mountain basins are key sources of runoff in many regions worldwide (Viviroli et al., 2007). Given the dominance of snow and ice melt, their hydrological budget is particularly vulnerable to climate change (Barnett et al., 2005). In particular, rapid ongoing and foreseen changes in the cryosphere in High Mountain Asia could have profound impacts on sensitive hydrosystems (Immerzeel et al., 2010).

Lake Issyk-Kul, an endoreic lake surrounded by the Teskey Ala Too and Kungei Ala Too mountain ranges in Central Asia, Kyrgyzstan (Figure 1), is the world's second largest high-altitude lake (1607 m a.s.l.) and one of the deepest (670 m deep) (Klerkx and Imanackunov, 2002; Romanovsky et al., 2013). Alongside its economic, social and heritage importance, it is also of great geographical interest because on the one hand, it is a large lake located far from any ocean and on the other hand, because thanks to thermal lifts, the lake never freezes.

Observations of the lake level over recent decades suggest that the water balance in Lake Issyk-Kul is changing due to the influence of both global climate change and the collapse of the Soviet Union (Delclaux et al., 2015; Alifujiang et al., 2021). On the one hand, climate change modifies evapotranspiration, precipitation, and snow and ice melt. On the other hand, the collapse of the Soviet Union resulted in degradation of irrigation networks in low elevation regions (Wegerich, 2004) leading to a significant reduction in withdrawals, but these increased again more recently with the restoration of part of the irrigated perimeters. However, separating the contribution of local and global changes to fluctuations in the level of Lake Issyk-Kul is complex since the water budget of the lake results from interplay between surface runoff and ground-water flow in the sub-basins, including seepage of groundwater into the lake itself (Mandychev, 2002; Alifujiang et al., 2017). Therefore, to understand the hydrological budget of Lake Issyk-Kul and potential future changes, the first step is characterizing the hydrological processes underway in areas upstream of any irrigation withdrawals. In these areas, it is also critical to accurately simulate snow and ice melt to explain variations in streamflow (Sorg et al., 2014; Duethmann et al., 2015). The challenge is the lack of hydrometeorological data in high elevation regions where most snow accumulates, thus hindering the calibration and evaluation of snow melt runoff models. Scientific interest in the hydro-glaciology of the Issyk-Kul lake tributaries catchments dates back to the Soviet era, but the results were only published locally (in Russian) and are not available to the international community. The present study and the one by Uwamahoro et al. (2021), in which the most recent tools and methods were used, therefore has a pioneering character, although it is important to note that data on the Kara-Batkak glacier have been published by World Glacier Monitoring Service for many decades (Zemp et al., 2021).

In this context, the Chon Kyzyl-Suu basin is of particular interest because data collected in multiple in-situ observations are available thanks to a network of stream gauges, meteorological stations as well as as mass balance surveys of Kara-Batkak glacier. These data enabled us to apply a distributed hydrological model to assess the basin water balance over a period of 10 years (2010-2020). Choosing the right model was a challenge; it had to convincingly deal with both snow-glacial processes and processes related to the water balance of a large lake, since the next step will be to extend its application to the entire Issyk-Kul lake basin. A Hydrological Distributed Snow Model (HDSM, Figure 2) was chosen because it was specifically designed for the study of large lakes and their basins (Le Coz et al., 2009; Bastola and Delclaux, 2012) as well as for the study of mountain processes (Savéan et al., 2015).

In the context of climate change, we also considered it important to explore what might happen in the near future in this benchmark sub-catchment using modeling, again with a view to later extrapolation to the entire basin of the large lake. To that end, we used the resulting model settings to evaluate the impact of climate change under two standard IPCC (*Intergovernmental Panel on Climate Change*) scenarios that are frequently used in this type of approach: ssp2-4.5 and ssp5-8.5 (IPCC, 2021; see section 1.6). The ssp2-4.5 scenario corresponds to a "business as usual" emission pathway with moderate greenhouse gas (GHG) emissions, the ssp5-8.5 scenario corresponds to increasing GHG emissions.

The paper is organized as follows. After a short description of the model and the study area, we present the available climate and hydrological data and future climate projections. The model results are presented in four sub-sections: (i) snow and ice melt, (ii) streamflow in the upper basins, (iii) streamflow in the entire Chon Kyzyl-Suu basin (iv) future hydrological trends. Finally, we discuss the uncertainties associated with these results and the key hydrological processes across the basin.

# 2. Material and method

## 2.1. Model description

HDSM (Figure 2) is spatially distributed as it performs all computations on a spatial grid. The main reasons for choosing this procedure are to account for the spatial variability of climatic forcing, the geomorphological structure of basins, and the dynamics of lakes or floodplains whose flooded area can vary greatly depending on bathymetry or relief. The basin is discretized in square cells as the forcing variables, not necessarily with the same resolution. The water balance is calculated for every cell, and the surface and groundwater flows are propagated toward the basin outlet. The output variables are also spatially distributed, thereby allowing extraction of the simulated flow at any location of the basin. One of the characteristics of the model is that it is possible to have soil cells or lake cells, or a mixture of the two, characterized by a coefficient varying between 0 (cell containing 100% soil) and 1 (cell containing 100% lake). Note that in HDSM terminology, the term “soil” includes the vegetation that covers it.

HDSM is conceptual as it uses a simplified representation of the hydrological processes to compute the water balance. This approach makes it possible to limit the number of the model parameters required for each cell. The parameterizations are derived from well-established hydrological models. The soil water balance is simulated using a GR4J (French abbreviation for *Agricultural Engineering, 4(parameters), Daily*) production function (Perrin et al., 2003). Snow and ice melt are computed using a degree-day method (Martinec and Rango, 1986). As a result of water production due to the balance between precipitation, snow and/or ice melt and evapotranspiration, the water content of a soil cell is divided into surface runoff and sub-surface runoff (or drainage). Each type of runoff is modeled using a reservoir law with its own specific residence time parameter. The sum of the two fluxes is then propagated to the downstream cell according to a transfer relationship similar to the uniform flow equation, but that vary depending on the slope.

To run the model, the user must provide a physiographic description of the basin including a digital elevation model and derived products (drainage direction, depression and lake areas, slope, aspect), glacier extent and surface pattern parameters (soil and vegetation). Meteorological data (air temperature, precipitation, reference evapotranspiration and open water evaporation) must be provided at a fixed time step, in this study, daily. All input data need to be distributed over the model grid.

However, despite its advantages, the choice of HDSM has one major drawback: the surface area of the glacier remains static over time. Consequently, the results of applying the model to long time intervals need to be interpreted with caution and this is undoubtedly a limit, although Puschiasis et al. (2022) did so in a previous study conducted in the Mount Everest region in Nepal. The limits of doing so in the present study are addressed in the discussion.

## 2.2. Study site: Chon Kyzyl-Suu sub-catchment

The Issyk-Kul Lake environment is characterized by a contrasted continental climate (Delclaux et al., 2015). At the elevation of the lake, mean annual precipitation varies strongly from west (~100mm/y) to east (~500mm/y) due to the combined influence of the mountains and of the lake on atmospheric water content; the monthly distribution shows the lowest precipitation amount in winter (December to February) and the highest in summer (June to September). The monthly mean temperature varies with an amplitude of more than 20°C between January (the coldest month) and July (the hottest).

The Chon Kyzyl-Suu river (Figure 3) is a south-east flowing tributary of Lake Issyk-Kul. Its downstream reach flows through the city of Kyzyl-Suu, 30 km south-west of the main district town, Karakol. Kyzyl-Suu (named Pokrovka in the Soviet era) is home to the Tien Shan High Mountain Scientific Center (TSHMSC), which is part of the National Academy of Sciences of the Kyrgyz Republic. The TSHMSC has an old tradition of mountain hydrology and glaciology research. It runs a long-term observatory of the Kara-Batkak glacier (Central Asia section in Zemp et al., 2021) and two weather stations in the upper valley of the Chon Kyzyl-Suu river.

For the current project, two existing hydrological stations that were previously observed manually, were equipped with automatic sensors in October 2015 and with data loggers in May 2016. The stations are located on the Kachkator water course, (the name of the upper reach of the Chon Kyzyl-Suu river). The upstream station, Istok, controls the flows of the Kara-Batkak glacier, just after crossing a moraine lake, and the downstream station, Ustya, controls more than 95% of the glaciated area of the Chon Kyzyl-Suu basin.

In addition, the Kyrgyz hydrometeorological agency, (hereafter "HydroMet"), runs one weather station in the city of Kyzyl-Suu and one hydrological station, named Lesnoi-Kardon, on the Chon Kyzyl-Suu river, upstream of the irrigation water intakes located between the piedmont and the lake.

Discharge data recorded at Lesnoi-Kardon (HydroMet) are available from 2012 to 2020 but include a two-year gap (May 2015-May 2017), at Ustya (for the present study), from 2016 to 2020, with yearly frozen periods from October to March, and at Istok (present study) from 2016 to 2019, with yearly frozen periods from October to April and a gap starting in 2020, due to technical failure of the sensor.

Three different digital elevation models, (SRTM – *Shuttle Radar Topography Mission*, GDEM – *Aster Global Digital Elevation Map* and ALOS – *Advanced Land Observing Satellite*), and two glacier data sets (the Randolf Glacier Inventory version 6 and the Gamdam Glacier Inventory) were tested with the aim of characterizing the basin and its two sub-basins. A preliminary analysis of these sources concluded that the combination of SRTM (http://srtm.csi.cgiar.org/srtmdata/) and RGI6 glacier data set (https://www.glims.org/RGI/) was the most appropriate for the present study.

The model grid resolution was set to 15 arcsecs (approximately 460 m) as a compromise between simulation accuracy and computing cost. In addition, the resolution of 15 arcsecs is close to that of the MODIS (*Moderate Resolution Imaging Spectroradiometer*; see following section) products used to evaluate the model. The characteristics of the three basins studied are summarized in Table 1.

The soil parameters in HDSM (Figure 2) are mainly descriptive (Hagemann and Gates, 2003; Hagemann and Stacke, 2015) and were kindly provided by Hagemann for our study area. This value is applied with a calibrated formula.

The present study was conducted at a daily time step covering the period 2010-2020, i.e. 11 calendar years, or 10 hydro-glaciological years. THMSC glaciologists in Kyrgyzstan base their work on a “glacier year” that runs from October to September. Weather data came from three stations (Figure 3), the first managed by HydroMet and the two other stations by TSHMSC:

- **Kyzyl-Suu** (78.02°E, 42.35°N, 1 765 m a.s.l.): air temperature and precipitation, with no gaps.
- **Chon Kyzyl-Suu Camp** (78.20°E, 42.19°N, 2 579 m a.s.l.): precipitation, with no gaps, air temperature (mean, minima and maxima), with a few gaps; atmospheric pressure, relative humidity and wind velocity at height of 0.5 m above the ground, with many gaps between 2012 and 2020.
- **Kara-Batkak** (78.27°E, 42.16°N, 3 286 m a.s.l.): air temperature and precipitation, only available between May and September from 2012 to 2020.

HDSM uses four types of climate data: air temperature, precipitation, reference evapotranspiration and open water evaporation. In this study, evaporation from the few local open waters is assumed to be equal to the reference evapotranspiration. The grid resolution of the spacialized climatology data is the same as the one chosen for the morphology, 15 arcsecs. The preparation of forcing involves three steps: (i) filling gaps in the time series; (ii) spatializing the temperature and precipitation data over the study basins at the modeling resolution; (iii) computing and spatializing the reference evapotranspiration.

- **Gap filling** (for details, see Supplemental Material, document 1). The gaps in the temperature time series were filled using elevation gradients established on a seasonal basis for winter (October to April) and summer (May to September). Gaps in precipitation were filled at Kara-Batkak weather station by regression using the data observed at Chon Kyzyl-Suu Camp.
- **Spatial distribution of air temperature and precipitation** (for details see Supplemental Material, document 1). Spatial distribution of temperature uses the same elevation gradient as that used for gap filling. Precipitation did not follow a linear relationship with elevation, so we used the formulae of Eeckman et al. (2017).
- **Computing and spatializing the reference evapotranspiration** (for details, see Supplemental Material, document 2). We used the Penman-Monteith equation (Allen et al., 1998) to compute a time series at Chon Kyzyl-Suu Camp. Gaps were filled using a regression between observations and the Copernicus ERA5 Land reanalysis (Munoz Sabater, 2019).

Finally, the parameters were calibrated through simulations using a set of random parameters generated with the Latin Hypercube Sampling method (McKay et al., 1979).

## 2.3. Method

The Table 2 presents a summary of the used data and their sources.

The first step of the HDSM modeling procedure consisted in setting the three snow parameters (degree-day factor, temperature and snow depth thresholds), for use in the following operations. Calibration consisted in optimizing the parameters by comparing the daily snow cover area (SCA) computed by HDSM with that recorded by the MODIS sensor. Parameter optimization was done at the scale of the Lesnoi-Kardon basin. Because of the lack of discharge data over a long interval in 2015-2017 and in order to be consistent with observations of the sub-catchment, calibration was based on the 2017-2020 period and validated using the period 2012-2016. The MODIS SCA was obtained from the daily Aqua and Terra MODIS snow products (MOD10A1 and MYD10A1). The two products were merged and gaps filled using the method of Gascoin et al. (2015).

The second step consisted in calibrating the two ice melt parameters (degree-day factor and temperature threshold). In the HDSM procedure, the remaining seasonal snow that accumulates over the glacier area is transformed into ice on October 1st. For the seven glaciological years 2013-2020, the TSHMSC reported an average annual net mass balance of -0.704 m water equivalent for the Kara-Batkak Glacier (Zemp et al., 2021). The ice melt parameters were calibrated assuming that all glaciers in the study basin have the same average annual net mass balance as the Kara-Batkak Glacier.

After setting the snow and ice parameters, the five main HDSM parameters of flow production were calibrated based on the river discharges recorded at the Ustya hydro station, and embedding the Istok headwater basin (Figure 3). Calibration covered the period 2017-2019. The best parameter set was then used for validation over the period 2016-2020 at Ustya and the period 2016-2019 at Istok. Applying the parameter set computed for the Ustya basin produced inconsistent results for the Lesnoi-Kardon basin. Consequently, a separate calibration/validation procedure was applied to this basin that accounted for the observed time series, and included the gap from May 20, 2015 until May 5, 2017. The period 2017-2020 was used for calibration and the period 2012-2015 was used for validation.

In addition, it should be noted that HDSM only works with time series with no gaps or in which the gaps have been filled. However, the watercourses of the headwater basins, Ustya and Istok, are superficially frozen in the winter season, making rigorous comparison between observed and simulated runoff impossible.

## 2.4. Future scenarios

To examine how climate change will affect the study area, we used the output of the CNRM-CMIP6-1 (*Centre National de Recherches Météorologiques – Coupled Model Intercomparison* Model) global circulation model (Voldoire et al., 2019). This was a good compromise in a study whose main aim is not to discuss the respective performances of different GCMs. Daily air temperature, precipitation and atmospheric pressure were downloaded from the Copernicus Climate Change Service (https://climate.copernicus.eu/). Calibration was performed to adapt the data sets at the Chon Kyzyl-Suu weather station site, based on the same 6-year period (2015-2020); calibration consisted of applying the parameters of the normal distribution function computed with the data of the present study to the CMIP6 data set at a daily time step.

HDSM assumes that the surface area of a glacier remains constant throughout the simulation period. We consequently restricted our climate projections to the period 2015-2060. The calibrated model was applied over both Ustya and Lesnoi-Kardon basins with the input data prepared as described above. To compute the reference evapotranspiration (ET0) with the Penman-Monteith formula, we used the method described in Supplemental Material document 2. However, wind velocities were not available from CNRM-CMIP6-1. Moreover, time series contained many long gaps that were impossible to fill. For lack of a better method, we applied a constant daily value of wind velocity equal to the mean of all values recorded 0.5 m above the surface of the ground.

# 3. Results

## 3.1. Present

**Snow melt and ice melt**

Figure 4 shows the simulated snow cover area compared with MODIS data. We used 3 criteria for calibration (cal) and calibration + validation (calval):

- Nash-Sutcliff (NS): cal = 0.84; calval= 0.86
- relative bias; cal = -0.002; calval = 0.026
- squared NS: cal = 0.84; calval = 0.84

The calibrated degree-day factor of snow melt is 4.2 mm/°C per day. The ice melt degree-day factor is 8.2 mm/°C per day, which gives an average annual net mass balance of -0.703 m wat. eq. per year for the glaciers in the Chon Kyzyl-Suu basin, and is identical to the mean observed net mass balance of the Kara-Batkak glacier in 2013-2020 (Figure 5). However, differences are apparent between the periods 2016-2017 and 2018-2019.

**Ustya and Istok sub-basins**

Figure 6 shows the observed vs HDSM discharge at Ustya and Istok, with calibration at Ustya and validation in both sub-catchments.

At Ustya, we obtained the following criteria:

- NS: cal = 0.65; calval= 0.56
- relative bias; cal = -0.004; calval = 0.112
- squared NS: cal = 0.71; calval = 0.60

At Istok, we obtained:

- NS:  calval= 0.66
- relative bias: calval = -0.136
- squared NS: calval = 0.62

However, the criteria values should be interpreted with caution, because they include the “frozen periods”, when discharge may occur under the frozen surface of the water course, but is not “monitored”.

Table 3 lists the annual values of the main hydrological variables after model calibration. The above computed net mass balance deficit of 0.703 m per year, also observed at Kara-Batkak glacier, at the Ustya basin scale (glacier area of 31.45 km²) corresponds to an ice-melt volume of 0.022 km$^3$ per year. This Figure is in line with the values listed in Table 3.

**Lesnoi-Kardon basin**

Applying the best parameter sets obtained in Ustya/Istok sub-basins to the Lesnoi-Kardon basin did not work satisfactorily. A new calibration of the complete basin was thus necessary, not including the results obtained for the sub-basins.

Figure 7 plots the comparison of the discharges observed at Lesnoi-Kardon and those obtained with HDSM applying the best parameter set and distinguishing calibration (2017-2020) from validation. We obtained:

- NS: cal = 0.50; calval= 0.51
- relative bias; cal = -0.038; calval = -0.009
- squared NS: cal = 0.58; calval = 0.58

The corresponding volumes of the main components of the water budget are summarized in Table 4. Comparison of tables 3 and 4 highlights huge differences in the computed ice melt volumes, whereas the glacier in the Lesnoi-Kardon basin is only 4.6% larger. These differences are discussed in the following section.

## 3.2. Future trends

The trends given by CNRM-CMIP6-1 are summarized in Table 5.

Based on the decade 2010-2020, the mean annual air temperature for the Ustya versus Lesnoi-Kardon basins will increase by respectively 0.81°C and 0.77°C in the decade 2050-2060 under scenario ssp2-4.5, and by respectively 1.70°C and 1.77°C under scenario ssp5-8.5.

The top part of Figure 8 shows future annual precipitation given by CNRM-CMIP6-R) with its linear adjustment in the two scenarios. Under scenario ssp2-4.5, no significant trend is visible, whereas under scenario 5-8.5, there is a decrease of 8.9% over the 40-year period.

Based on the decade 2010-2020, the mean annual reference evapotranspiration for the Ustya and the Lesnoi-Kardon basins will increase by respectively, 2.2% and 2.0% in the decade 2050-2060 under scenario ssp2-4.5, and by respectively, 7.0% and 6.5% under scenario ssp5-8.5.

The set of calibrated parameters for the Ustya basin on the one hand and for the Lesnoi-Kardon basin on the other hand, were then applied using the climate data obtained from the CNRM-CMIP6-1 for the two scenarios, ssp2-4.5 and ssp5-8.5, for the period 2010-2060 (glacier years). Table 6 and Table 7 summarize the results, which are discussed in the following section.

# 4. Discussion

## 4.1. Uncertainties

Beven (2016) discussed different facets of the uncertainty concept in hydrological studies and distinguished several types of uncertainty. Almost all also apply to the present study:

- **Uncertainties due to observed data**: this concerns the intrinsic quality and the processing of the local observed data, including filling gaps in the time series.

- **Uncertainties due to spatial representation**: basically, this concerns the spatialization methods used for the climate data, which originates from a small number of weather stations (3 in the present study) and on orographic behaviors (Eeckman et al., 2017), but also on the spatial resolution chosen, which is based on computing considerations.
- **Uncertainties due to modeling**: Two types of model are used in the present study: (i) representing hydrological processes: the HDSM model introduces a set of calibrated parameters, not all independent, and fixes a frame of relations between the water balance elements (Figure 2), which cannot avoid an equifinality issue (Beven, 2006) in its "setting configuration"; (ii) assessing climate scenarios: only one *Global Circulation Model* is considered here, with its own quota of assumptions and internal computing methods (Voldoire et al., 2019).
- **Uncertainties due to missing knowledge**: A key element of the water processes in the basin, groundwater flows, is not known, even though the numerous glacier deposits, screes or moraines, the flat grasslands, often containing areas of peat, and the presence of a thermal resurgence are evidence for, among others, intense groundwater fluxes, including at considerable depth. Concerning the hydrological and glaciological processes, it should be noted that two additional elements were not considered in this study: permafrost or temporary frozen soils on the one hand, sublimation in the other. This problem is similar to that of groundwater flows: no field observations are available. It should thus be considered that the frozen soil issue is included in drainage and that sublimation is included in evapotranspiration.

With the exception of local field data (meteorology, hydrology and glaciology) and remote sensing data (basically, basin physiography, snow cover dynamics and glacier extent), most of these uncertainties cannot readily be quantified in the Chon Kyzyl-Suu basin. However, all remote sensing data are subject to post-processing, which could affect their reliability.
The data provided by HydroMet, a third party of the project, require a special mention. Although the weather data are direct observations and are locally comparable with similar observations in the same context, this is not the case of the discharge data at the Lesnoi-Kardon hydrological station as we were unable to obtain information on how they were established from the water levels, meaning that the hydrological processes reported are likely, but, without the possibility to quantify a rigorous confidence level, not 100% reliable. This also implies that our discussion of future scenarios is incomplete and surprises may be in store.

## 4.2. Present

**Snow cover area**

HDSM represents the snow cover dynamics rather well (Figure 4). In their study using the SWAT model, Uwamahoro et al. (2021) found a snow melt degree-day factor of 4.3 mm/°C per day in the Barskoon basin located a short distance from the Chon Kyzyl-Suu basin, while the value calibrated in the present study using HDSM is 4.2 mm/°C per day. The similarity is remarkable, especially given the notable differences between the two approaches: modeling tools (SWAT – *Soil and Water Assessment Model* vs HDSM), calibration time and duration (2015 vs 2017-2020) and the size of the basins (2 165 vs 308 km²). These values are nevertheless within the range of mean values reported in the literature (Rango and Martinec, 1995; Hock, 2003).

**Glacier dynamics**

As highlighted in the description of the model in section 2.1, the dynamics of glacier extension cannot be represented with HDSM, although for a 10-year period of application, it can be disregarded. However, the representation of variations in the mass balance remains reliable. Brun et al. (2017), assessed the net mass loss of the glaciers in the Tien Shan mountains in recent years to range from 0.6 to 1.0 m water equivalent per year, with a continuous increase since 2000, in agreement with Figure 5 and in line with results obtained at the scale of the Chon Kyzyl-Suu basin (0.7 m water equivalent per year). Barandun et al. (2020) and Barandun et al. (2021) undertook a comparable analysis, also including the net mass balance of the Kara-Batkak Glacier.

**Hydrological processes**

At first glance, the two models and their distinct parameter sets for surface runoff appear to offer a robust first approach to the Lesnoi-Kardon basin (Figure 7) including its embedded basins, Ustya and Istok (Figure 6), although the NS and squared NS criteria are not 100% satisfactory due to the approximate reproduction of low and peak discharges by HDSM and also to the frozen sequences. However, this result masks significant differences reflected by anomalies for the Lesnoi-Kardon basin:

- We already mentioned the problem with the 4- or 5-times higher ice melt volume modeled even though the glaciated area is not significantly larger. This also increases the ice melt degree-day-factor from 8.2 mm/°C per day to 13.3 mm/°C per day.
- The residence time of runoff in the surface reservoir is multiplied by approximately 10, or by 2 in the subsurface reservoir (Figure 2).
- High runoff coefficients are observed, sometimes greater than 1, which is not aberrant in snowy and glaciated environments, as analyzed by Favier et al. (2009).

Possible explanations for this concrete situation are:

- Overestimation of the observed discharges at Lesnoi-Kardon in data provided by a third party, resulting from inaccurate water level records, or when drawing the rating curve, or both.
- A huge role played by circulating groundwater that cannot be monitored in the field and is only roughly represented in the HDSM model.
- Piecemeal spatial and temporal information concerning precipitation above 3 300 m a.s.l.

The absence of additional data means it is currently impossible to satisfactorily and rigorously solve the enigma surrounding this process. Nevertheless, it should be noted that the precipitation estimated at high elevations worked correctly in the case of the Ustya and Istok basins.

Based on the above limitations, it is prudent to limit our concluding analysis to the headwater basins, which do not invite serious criticism.

## 4.3. Future trends

Applying future scenarios ssp2-4.5 and ssp5-8.5, as proposed by the "CNRM-CMIP6-1" datasets (Voldoire et al., 2019) resulted in the annual values of the main components of the water balance presented in tables 5, 6 and 7, and for precipitation, in Figure 8. Limiting our analysis to the Ustya basin, we can make the following comments:

- Real evapotranspiration, driven by the available amount of precipitated water, will not significantly affect groundwater in the next 40 years.
- Under the two scenarios, air temperature will increase by respectively, 0.8°C and 1.7°C, and reference evapotranspiration will increase respectively, by 2.2% and 7.0%.
- Although under scenario ssp2-4, there will be no noticeable change in precipitation, under scenario ssp5-8.5 there will be an 8.9% reduction over the coming 40 years, which reaches 16.3% when only precipitation in the form of snow is taken into account (Figure 8 bottom panel) linked with increasing temperature.
- The annual volume of snow melt will decrease slightly, by respectively 3.3% and 8.8% under the two scenarios over the 40-year period. When the uncertainties inherent in this type of approach are taken into consideration, this result is comparable with the previous one.
- In contrast, under both scenarios, the increase in ice melt is slower in the first half than in the second half of the 40-year period, it reaches 25% under the ssp2-4.5 scenario and more than 100% under ssp5-8.5.
- Maximum daily means per decade (Table 7) revealed no clear trends for snow and ice melt.
- Finally, all the above-mentioned conditions increase the annual discharge by, respectively, 13%, and 28% under the two scenarios. The increase is driven by ice melt that produces an annual average excess discharge (Radić and Hock, 2014). A similar increase can be observed in the daily maximum discharge per decade. But these trends and figures should be interpreted with caution, since they are based on the assumption the glaciers will still be able to supply such volumes (Chevallier et al., 2011; Chevallier et al., 2014) which is far from guaranteed.

Duethmann et al. (2015) analyzed trends in stream flows in the Tarim basin, located south of and opposite the Issyk-Kul basin, using the WASA (*Model for Water Availability in Semi-Arid Environment*) model (Güntner et al., 2004). These authors reported that glacier melt increased discharge by a factor ranging from 13% to 29% over the period 1957-2004. For a comparable duration, their figures are almost identical to ours.

# 5. Conclusion

The results reported in this paper are not only in line with existing works on the same region, but additionally underline the importance of underground circulation, although unfortunately without being able to represent and quantify it in concrete terms. What is more, the results underline the ability of a distributed conceptual model to account for the complexity of water processes in a mountain environment with a poor operational field dataset.

This study is an important step forward on the way to a full model of the entire Lake Issyk-Kul basin. The HDSM parameters calibrated on the Chon Kyzyl-Suu basin can be extended to the other mountain water courses that contribute to the lake balance. Weaknesses and uncertainties encountered at the Chon Kyzyl-Suu sub-catchment scale should be smoothed out at the lake scale, particularly the dynamics of the glacier extension processes that could not be modeled by HDSM. It will indeed be necessary to use a larger grid resolution. It should also be noted that two additional elements require careful scrutiny at the scale of the lake: the sub-surface exchanges between groundwater and lake water, and the role played by irrigation withdrawals. Some attempts to assess the contribution of the latter are promising, based on remote sensing analysis (https://labo.obs-mip.fr/multitemp/an-overview-of-irrigation-evolution-in-central-asia-with-landsat/).

Compared with other mountain ranges where the cryosphere is crucial for the future of water resources in Europe, North America, New Zealand, and also to some extent in the Andes and Hindukush Himalaya, the Central Asian region is still poorly studied and little instrumented, despite notable attempts, in particular by Chinese research projects. This study adds to our current knowledge of the cryospheric processes but underlines the numerous uncertainties surrounding hydrological slope processes and the need for more field exploration.

Finally, this study makes it possible to envisage realistic modeling with a daily time step at the scale of the basin and simulations of the lake levels in future scenarios.

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# Table captions

1. Basin characteristics computed with SRTM at 15 arcsecs and RGI6.
2. Summary of data used and sources.
3. Mean annual values of simulated hydrological variables at Ustya for the period 2016-2020.
[Ta = mean annual air temperature over the basin. Pr = full precipitation, ET0 = reference evapotranspiration (Penman-Monteith), RET = real evapotranspiration, Q = discharge]
4. Simplified annual water balance at Lesnoi-Kardon for the glacier years 2012 to 2020.
[Ta = mean annual air temperature for the entire basin. Pr = full precipitation, ET0 = reference evapotranspiration (Penman-Monteith), RET = real evapotranspiration, Q = discharge, obs = observed data, HDSM = HDSM simulation.]
5. Ustya and Lesnoi-Kardon basins: annual mean climate data for CNRM-CMIP6 scenarios ssp2-4.5 and ssp5-8.5
6. HDSM simulation with CNRM-CMIP6 scenarios ssp2-4.5 and ssp5-8.5. Simplified annual water balance on the Ustya and Lesnoi-Kardon basins for the decades 2010-2020 (present), 2030-2040 and 2050-2060. [RET=real evapotranspiration]
7. Ustya basin: Maximum daily means of snowmelt, ice melt and discharge under CNRM-CMIP6 scenarios ssp2-4.5 and ssp5-8.5, for the decades 2020 to 2060.

# Figure captions

1. Upper panel: map of Kyrgyzstan. Lower panel: map of Issyk-Kul Lake basin showing the Chon Kyzyl-Suu basin. Projection: WGS84, UTM zone 43N.
2. Flow chart of the HDSM model in the absence of a lake..
[RET = real evapotranspiration; $ET_0$ = reference evapotranspiration; Ta = air temperature; P = precipitation]
3. Chon Kyzyk Suu River basin. Projection: WGS84, UTM zone 43N.
4. Calibration / Validation of the daily snow cover area in the Lesnoi-Kardon basin using the HDSM model.
[1.Obs = MODIS product, 2. Calibration=HDSM calibration (2017-2020), 3. Validation=HDSM validation (2012-2016)]
5. Comparison of the observed annual net mass balance of the Kara-Batkak Glacier and the simulated balance for the glaciers in the Chon Kyzyl-Suu basin (Oct. 2013-Sept. 2020). The line represents the identical average of both time series.
6. Calibration / Validation of the daily discharge at Ustya and Istok hydro stations using the HDSM model.
[1.Obs = observed discharge, 2. Calibration=HDSM calibration (2017-2019), 3. Validation= HDSM validation (2016 & 2020 at Ustya; 2016 at Istok)].

7. HDSM: calibration / validation of the daily discharge at Lesnoi-Kardon hydro station.

[1.Obs = observed discharge, 2.HDSM=HDSM calval]

8. Annual volume of precipitation under the CNRM-CMIP6 scenarios ssp2-4.5 and ssp5-8.5, during the period 2010-2060 (2010-2020 are observed data). Upper panel: full precipitation (rain+snow); Lower panel: snow precipitation.

Table 1



| Basin | River | Outlet | | Altitude (min/max) (m) | Area (km²) | |
|---|---|---|---|---|---|---|
| | | Longitude (deg E) | Latitude (deg N) | | Total | Glaciers |
| **Lesnoi-Kardon** | **Chon Kyzyl-Suu** | 78.0920 | 42.2999 | 1963/4751 | 308.3 | 32.92 (10.8%) |
| **Ustya** | **Kachkator** | 78.2015 | 42.1912 | 2582/4751 | 166.4 | 31.45 (19.3%) |
| **Istok** | **Kachkator** | 78.2660 | 42.1627 | 3255/4363 | 6.854 | 2.335 (32.1%) |

| **Data used** | **Sources (referenced in the text)** |
|---|---|
| Physiography | |
| Digital Elevation Model | Shuttle Radar Topography Mission |
| Glacier extent | Randolf Glacier Inventory |
| Points of Interest | Open Street Map & ESRI |
| Land cover | kindly provided by Hagemann (personal comm.) |
| Local climate | |
| Kyzyl Suu | Kyrgyz Hydro-Meteorological Agency |
| Chon Kyzyl Suu Camp & Karabatkak | Tien Shan High Mountain Scientific Centre |
| Regional climate | |
| Reanalysis | Copernicus ERA 5 Land |
| Global Climate Model | CMIP6 – CNRM (France) |
| Hydrology | |
| Lesnoi Kardon | Kyrgyz Hydro-Meteorological Agency |
| Ustya & Istok | Tien Shan High Mountain Scientific Centre |
| Snow and Ice | |
| Snow cover extent | Moderate Resolution Imaging Spectroradiometer |
| Karabatkak glacier | Tien Shan High Mountain Scientific Centre & World Glacier Monitoring Service |

Notes: Spatial data were processed with QGIS (https://www.qgis.org/) and hydro-meteorological time-series with the R package “htsr” (https://CRAN.R-project.org/package=htsr).

| years | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|
| Ta (°C) | -5.88 | -6.65 | -6.92 | -6.12 | -6.61 |
| Pr (mm/y) | 1081 | 715 | 751 | 673 | 968 |
| ET0 (mm/y) | 402 | 414 | 414 | 402 | 414 |
| RET (mm/y) | 192 | 174 | 180 | 180 | 192 |
| Snow melt ($km^3/y$) | 0.101 | 0.093 | 0.079 | 0.08 | 0.102 |
| Ice melt ($km^3/y$) | 0.021 | 0.029 | 0.026 | 0.045 | 0.023 |
| Q ($km^3/y$) | 0.097 | 0.097 | 0.073 | 0.095 | 0.093 |
| Runoff coeff. | 54.1% | 81.8% | 58.4% | 85.0% | 58.0% |

| Glacier years | | 2012-13 | 2013-14 | 2014-15 | 2015-16 | 2016-17 | 2017-18 | 2018-19 | 2019-20 |
|---|---|---|---|---|---|---|---|---|---|
| Ta (°C) | | -3.70 | -4.24 | -3.81 | -2.91 | -4.01 | -3.79 | -3.67 | -3.50 |
| Pr (mm/y) | | 723 | 467 | 707 | 889 | 704 | 636 | 545 | 837 |
| ET0 (mm/y) | | 512 | 496 | 506 | 506 | 487 | 493 | 487 | 493 |
| RET (mm/y) | | 308 | 302 | 292 | 308 | 285 | 302 | 298 | 292 |
| Snow melt ($km^3$/y) | | 0.130 | 0.091 | 0.142 | 0.142 | 0.135 | 0.111 | 0.108 | 0.141 |
| Ice melt ($km^3$/y) | | 0.087 | 0.111 | 0.116 | 0.080 | 0.101 | 0.090 | 0.136 | 0.084 |
| Q ($km^3$/y) | obs | 0.224 | 0.157 | | | | 0.226 | 0.206 | 0.209 |
| | HDSM | 0.209 | 0.212 | 0.232 | 0.208 | 0.223 | 0.207 | 0.223 | 0.219 |
| Runoff coeff. (%) | obs | 100 | 109 | | | | 115 | 123 | 80.7 |
| | HDSM | 93,7 | 147 | 106 | 75.9 | 103 | 106 | 133 | 84.6 |

| basin | data | scenario | 2010-20 | 2020-30 | 2030-40 | 2040-50 | 2050-60 | diff |
|---|---|---|---|---|---|---|---|---|
| Ustya | Tair (°C) | ssp2-4.5 | -6.44 | -6.26 | -6.15 | -5.93 | -5.63 | 0.81°C |
| | | ssp5-8.5 | | -6.24 | -6.00 | -5.61 | -4.74 | 1.70°C |
| | Pr (mm/y) | ssp2-4.5 | 825.2 | 789.0 | 834.2 | 738.8 | 859.5 | |
| | | ssp5-8.5 | | 815.6 | 911.7 | 823.0 | 731.9 | |
| | ET0 (mm/y) | ssp2-4.5 | 532.5 | 535.2 | 541.3 | 546.6 | 544.3 | 2.2% |
| | | ssp5-8.5 | | 533.2 | 536.3 | 550.1 | 569.6 | 7.0% |
| Lesnoi-Kardon | Tair (°C) | ssp2-4.5 | -3.68 | -3.50 | -3.34 | -3.15 | -2.91 | 0.77°C |
| | | ssp5-8.5 | | -3.48 | -3.26 | -2.81 | -1.91 | 1.77°C |
| | Pr (mm/y) | ssp2-4.5 | 710.4 | 680.1 | 718.9 | 636.2 | 740.7 | |
| | | ssp5-8.5 | | 703.2 | 785.5 | 709.2 | 630.5 | |
| | ET0 (mm/y) | ssp2-4.5 | 573.4 | 575.8 | 581.9 | 587.0 | 584.9 | 2.0% |
| | | ssp5-8.5 | | 573.8 | 577.1 | 590.9 | 610.6 | 6.5% |

***Notes***: *Tair in averaged °C, Pr and ET0 in cumulated mm/y; Tair diff is the absolute difference in °C between the decades 2010-20 and 2050-60; ET0 diff is the relative difference between the decades 2010-20 and 2050-60.*

| basin | variable | scenario | 2010-20 | 2030-40 | 2050-60 | diff(*) |
|---|---|---|---|---|---|---|
| Ustya | RET | ssp2-4.5 | 0.031 | 0.032 | 0.030 | |
| | | ssp5-8.5 | | 0.028 | 0.033 | |
| | Snow melt | ssp2-4.5 | 0.091 | 0.085 | 0.088 | -3.3% |
| | | ssp5-8.5 | | 0.097 | 0.083 | -8.8% |
| | Ice melt | ssp2-4.5 | 0.028 | 0.043 | 0.035 | 25% |
| | | ssp5-8.5 | | 0.029 | 0.061 | 110% |
| | Discharge | ssp2-4.5 | 0.088 | 0.091 | 0.099 | 13% |
| | | ssp5-8.5 | | 0.099 | 0.113 | 25% |
| Lesnoi-Kardon | RET | ssp2-4.5 | 0.092 | 0.097 | 0.095 | |
| | | ssp5-8.5 | | 0.092 | 0.104 | |
| | Snow melt | ssp2-4.5 | 0.126 | 0.110 | 0.114 | |
| | | ssp5-8.5 | | 0.127 | 0.104 | |
| | Ice melt | ssp2-4.5 | 0.096 | 0.115 | 0.126 | |
| | | ssp5-8.5 | | 0.103 | 0.198 | |
| | Discharge | ssp2-4.5 | 0.208 | 0.203 | 0.206 | |
| | | ssp5-8.5 | | 0.202 | 0.272 | |

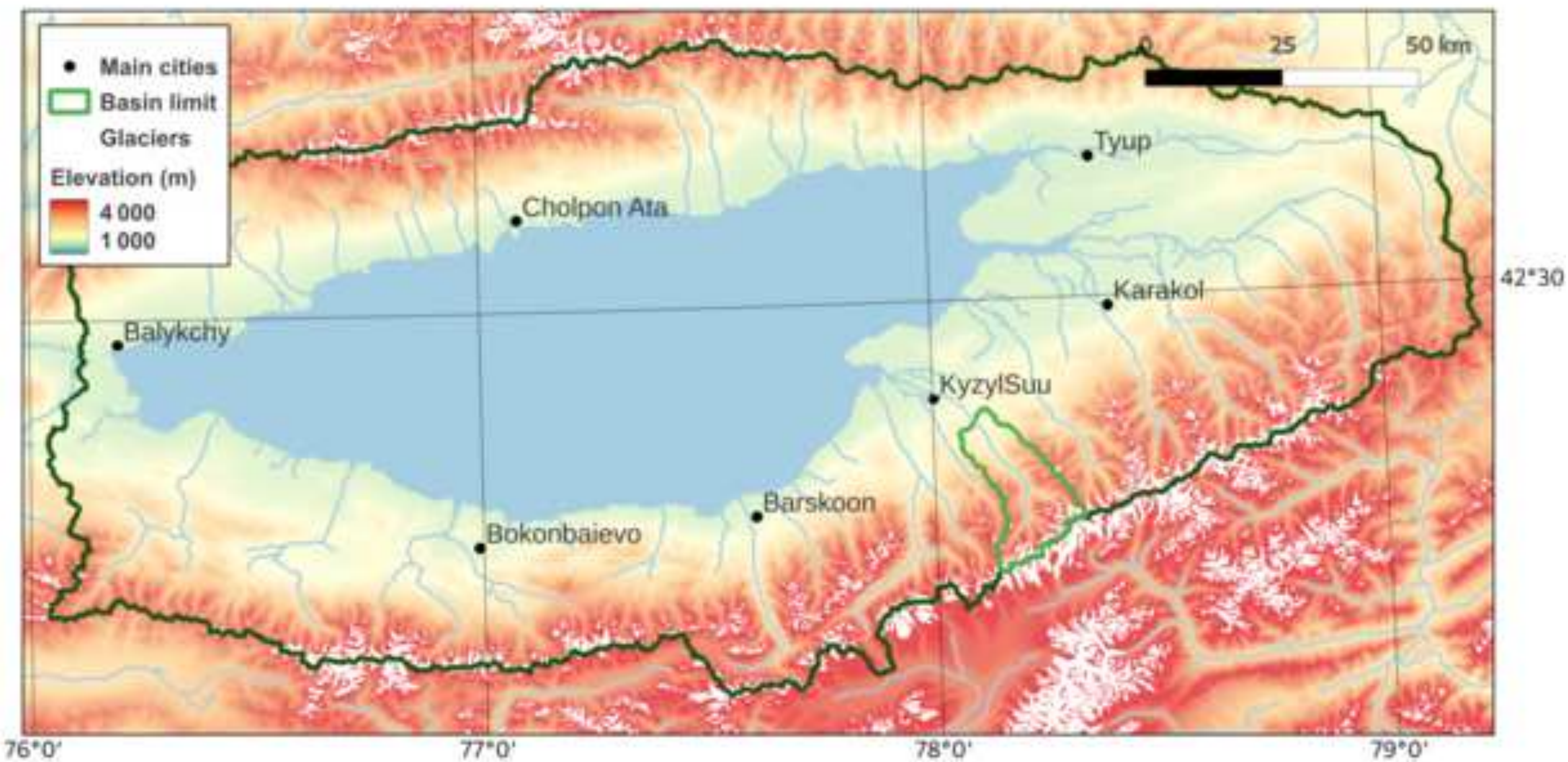
**Notes:** data in $km^3/y$, except for diff; diff is the relative difference of the decade 2050-2060 with the decade 2010-2020, not computed for Lesnoi-Kardon, due to the inconstancy observed for this basin.

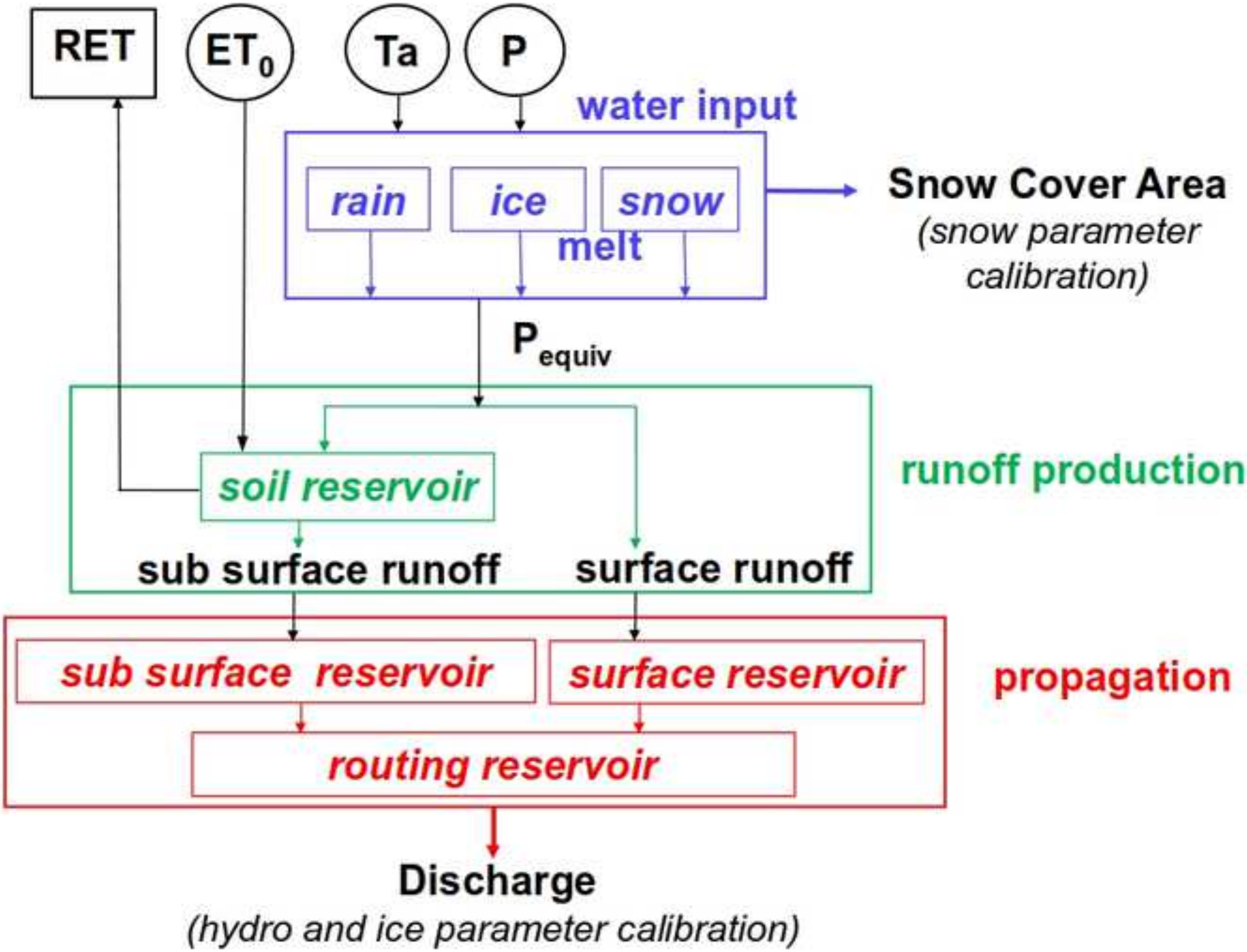
| basin | variable | scenario | 2020-30 | 2030-40 | 2040-50 | 2050-60 |
|---|---|---|---|---|---|---|
| Ustya | Snow melt (m3/s) | ssp2-4.5 | 26.8 | 20.8 | 30.6 | 28.5 |
| | | ssp5-8.5 | 26.8 | 26.8 | 30.0 | 20.0 |
| | Ice melt (m3/s) | ssp2-4.5 | 13.1 | 12.7 | 13.2 | 13.9 |
| | | ssp5-8.5 | 10.8 | 11.4 | 14.8 | 15.8 |
| | Discharge (m3/s) | ssp2-4.5 | 17.6 | 19.3 | 20.5 | 23.1 |
| | | ssp5-8.5 | 21.9 | 20.6 | 18.2 | 28.6 |

Figure 1



Fig1-rev.png


RET
ET0
Ta
P
water input
rain
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snow
melt
Snow Cover Area
(snow parameter calibration)
Pequiv
soil reservoir
runoff production
sub surface runoff
surface runoff
sub surface reservoir
surface reservoir
propagation
routing reservoir
Discharge
(hydro and ice parameter calibration)

Figure 3 Click here to access/download;Figure;Fig_3.tif

Fig_3.png

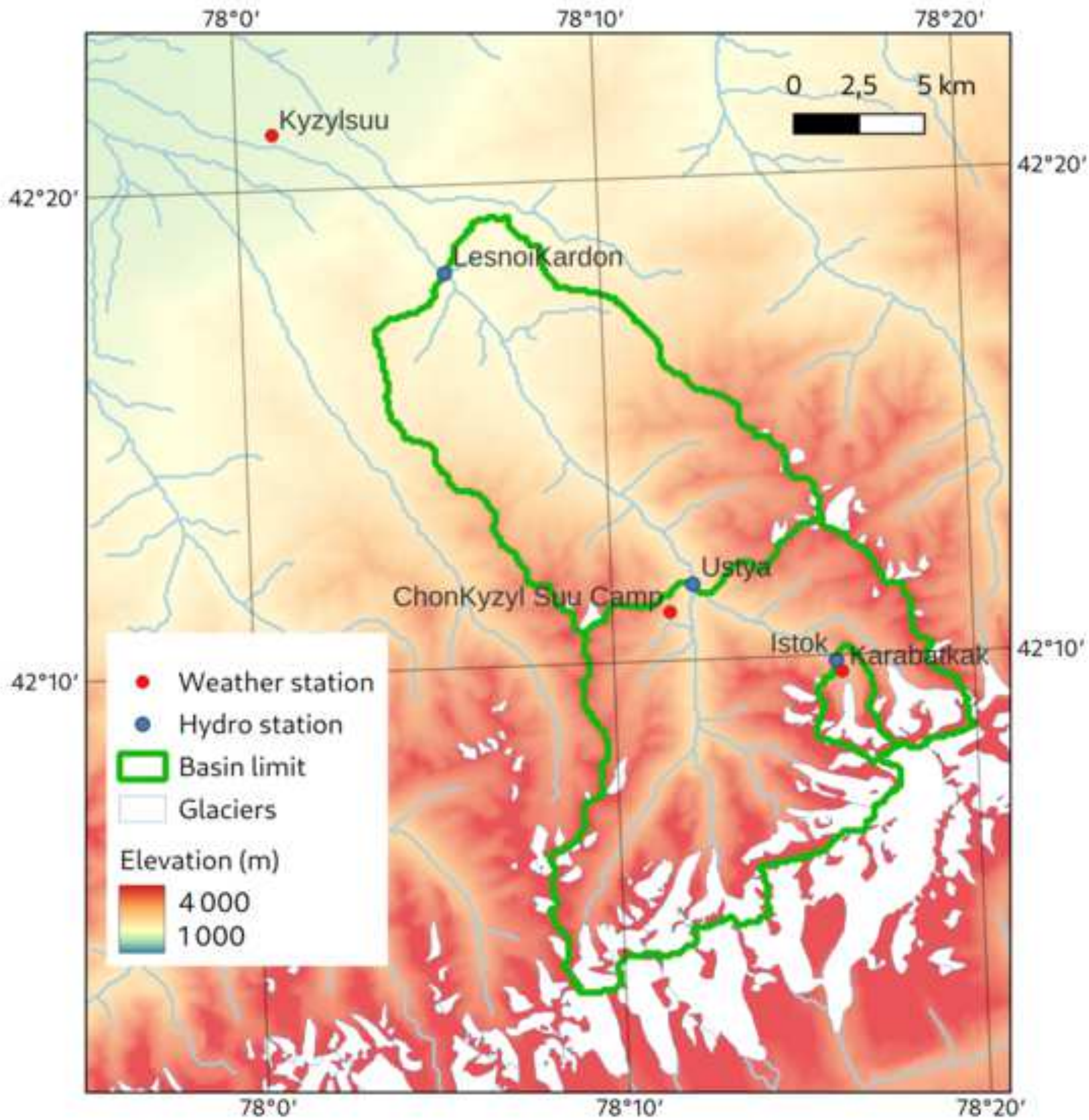

Figure 4

Click here to access/download;Figure;Fig_4-rev2.tif

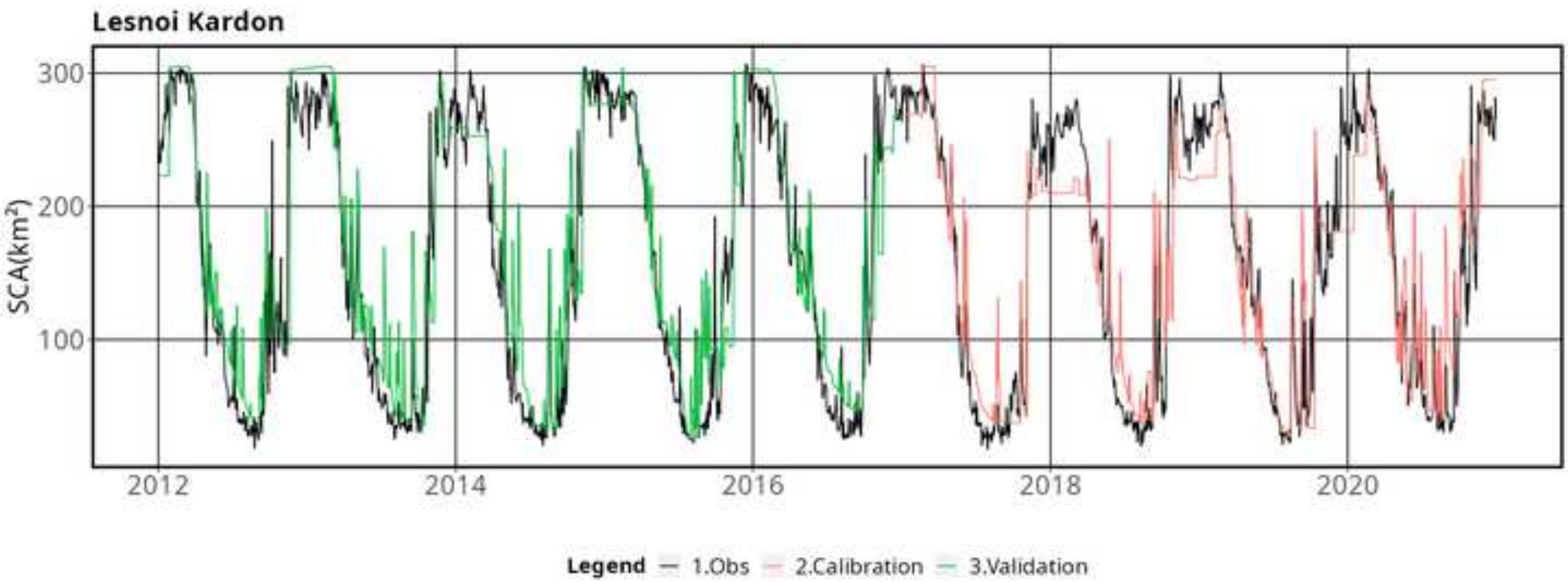


Fig_4-rev2.png

Figure 5



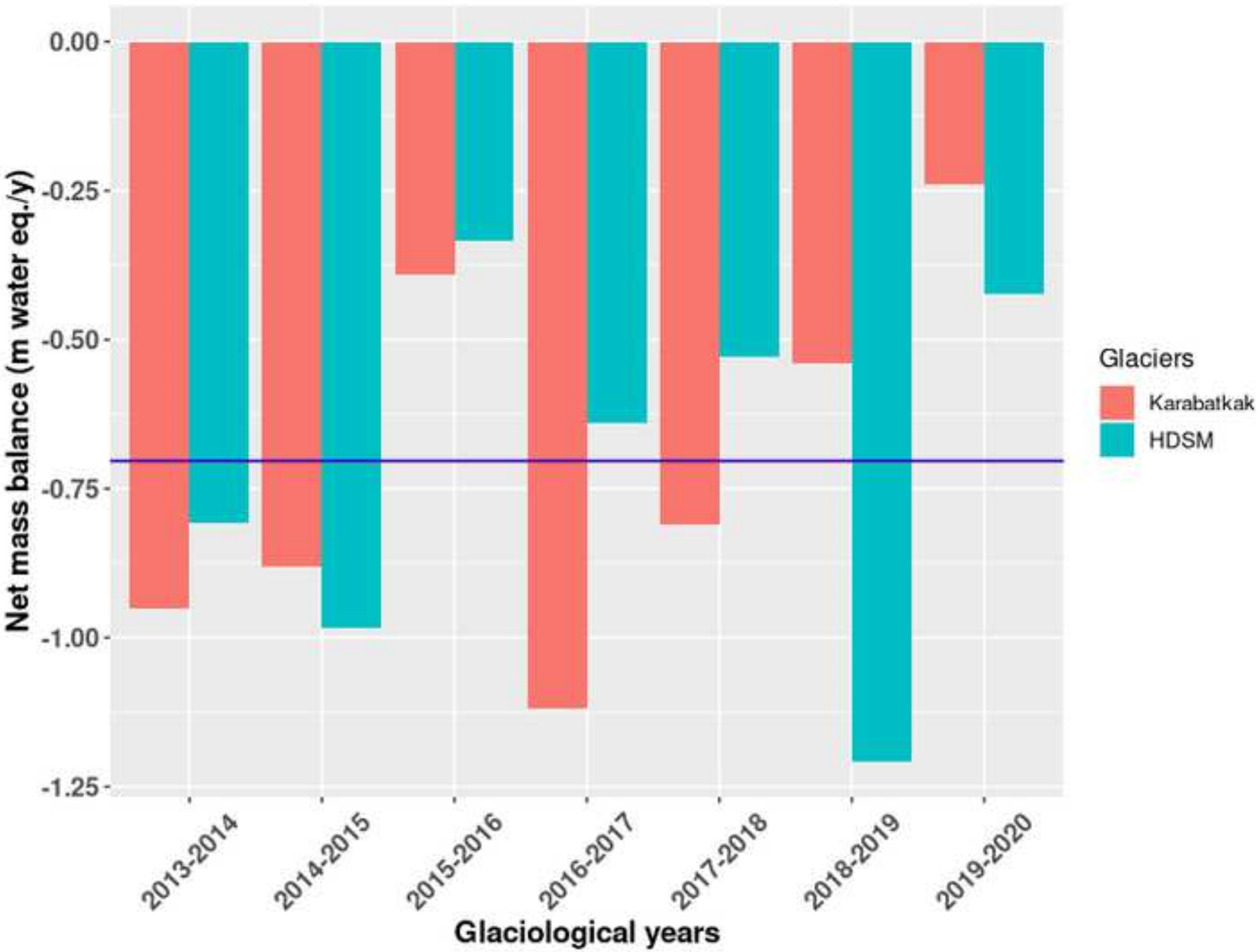


Fig_5.png

Figure 6



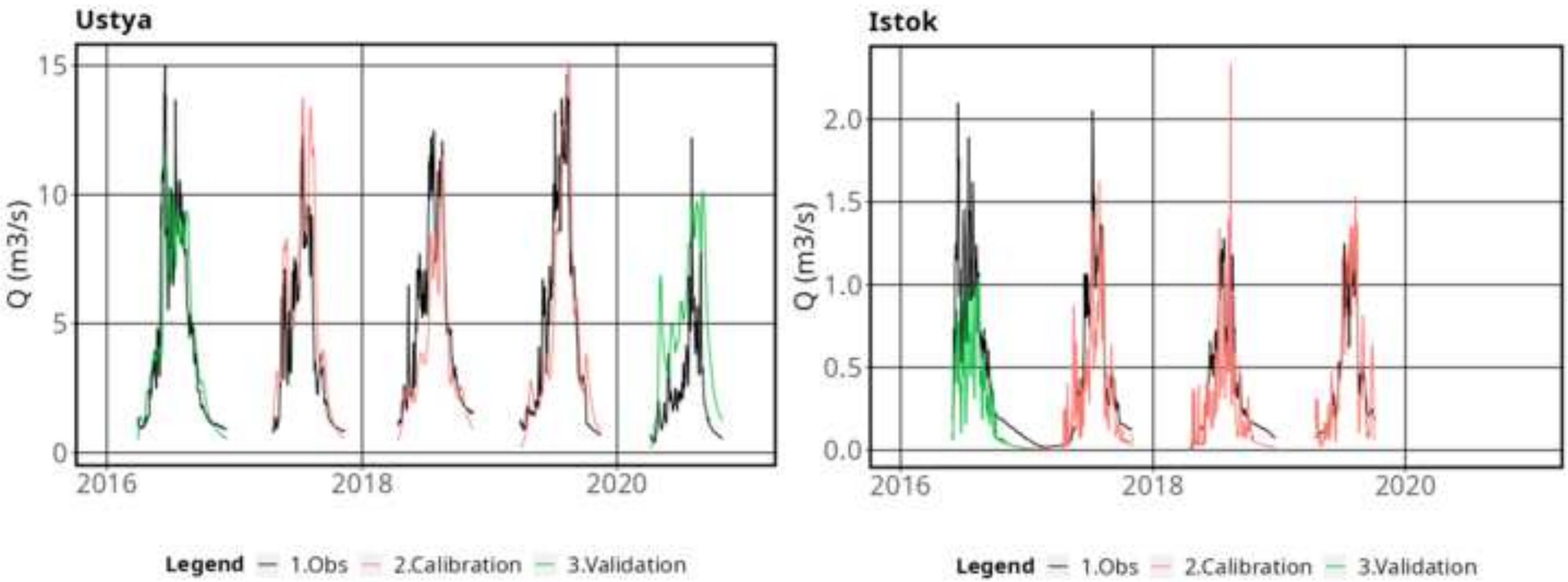


Fig_6-rev2.png

Figure 7

Click here to access/download;Figure;Fig_7-rev2.tif

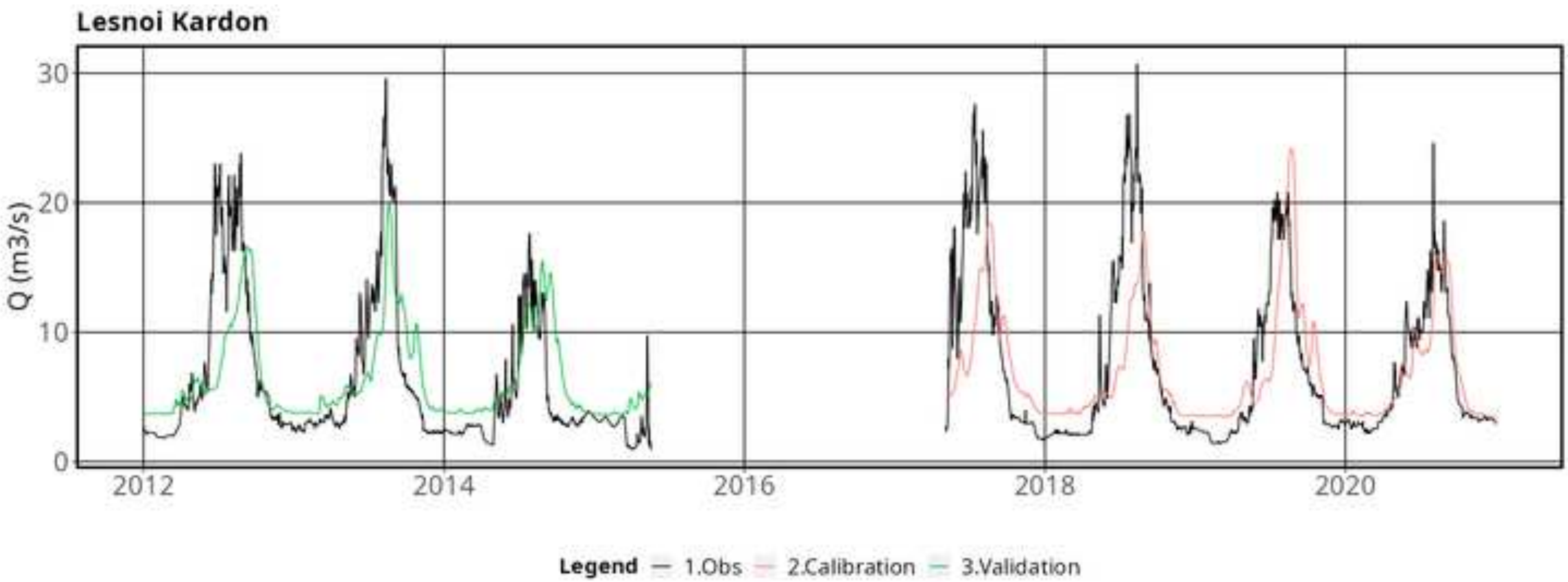


Fig7-rev2.png

Figure 8

Click here to access/download;Figure;Fig_8-rev2.tif

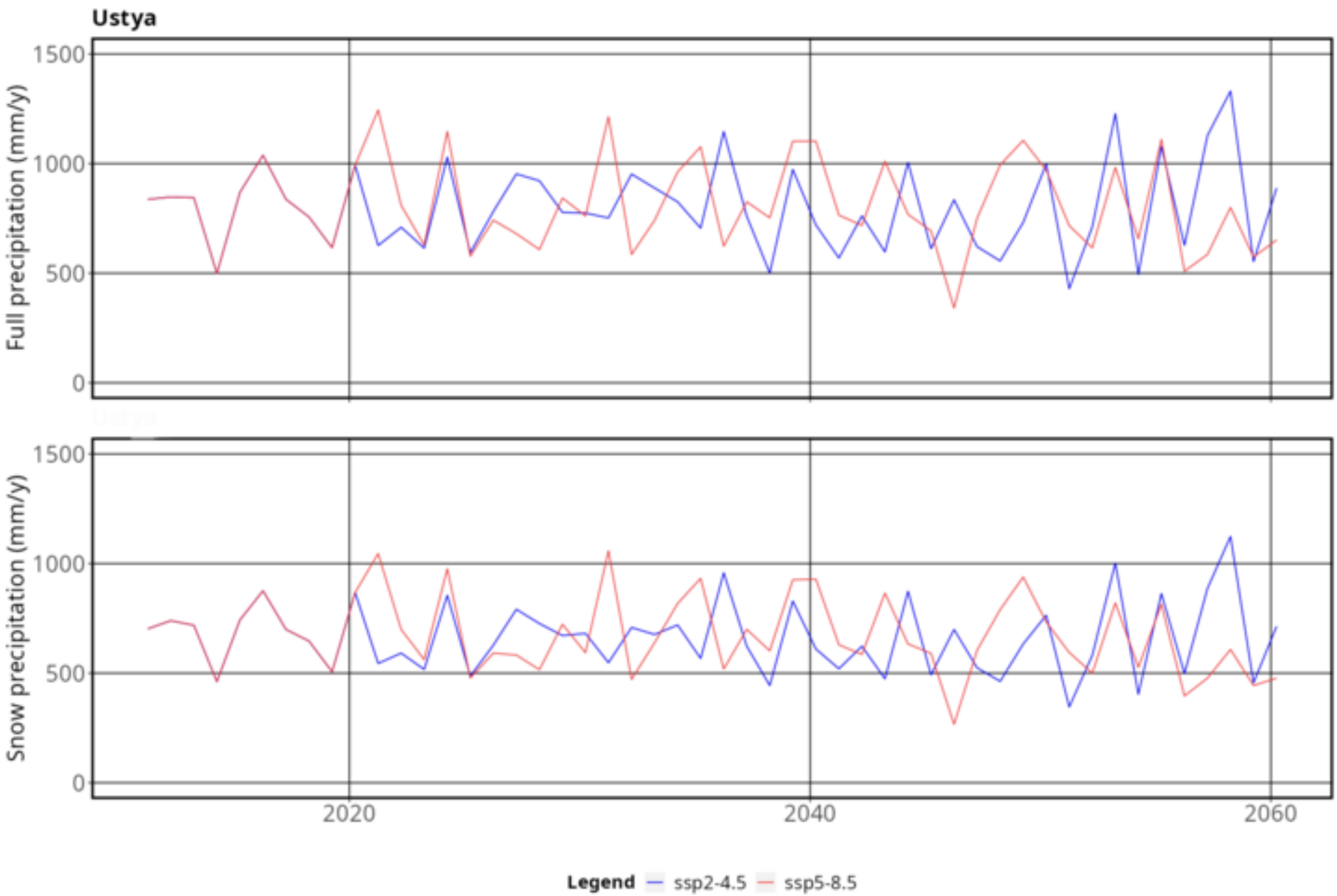


Fig_8-rev2.png