The impact of climate change on surface water quality
in the Amu Darya basin Project

Analysis of the water quality parameters in the Amudarya River

Analytical Report

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1 Introduction

The Amu Darya River basin (Figure 1), with approximately 310 000 km^2 (excluding Zeravshan - which practically does not reach the Amu Darya stream anymore) is one of the main water sources of Central Asia. The Amu Darya River takes its beginning at the conjunction of Vahsh and Pianj rivers on the territory of Tajikistan, which, in turn, originate in the Tien Shan and Pamir mountains. The total length of the river is 1,415 km (2, 620 km including Pianj River) and mean annual discharge is around 2000 m^3/s. The main tributaries are Vahsh River, Surkhandarya River, Sherabad River, Zeravshan River – right bank; Pianj River and Kunduz – left bank. The major part of water resources of the Amu Darya is formed on the territory of Tajikistan; in the middle part of the river it receives water from the Kafirnigan and Surkhandarya Rivers, while in the downstream reach the river has no further tributaries. The average rainfall in the downstream part, in the steppe is approximately 200-300 mm a year. Main water user in the Amu Darya River basin is agriculture, which relies nearly to a full extent only on the irrigation.

Figure 1 The Amu Darya River basin

The Amudarya system is highly dependent on the changes in the glacier mass balances and snowmelt processes as nearly all of the water resources of the Amu Darya River are originating from the high-ranges of the Tian Shan and Pamir mountains. The river flow is therefore characterized by strong seasonality, with peak flows occurring in summer, reaching their maximum in July when glacier melt is at its maximum, as presented in Figure 2. The minimum river discharge occurs in January – February. Only the Kafirnigan River tributary has slightly different discharge dynamics, with peak flow occurring in May, as this river is driven to a larger extent by snowmelt and not by glacier melt.

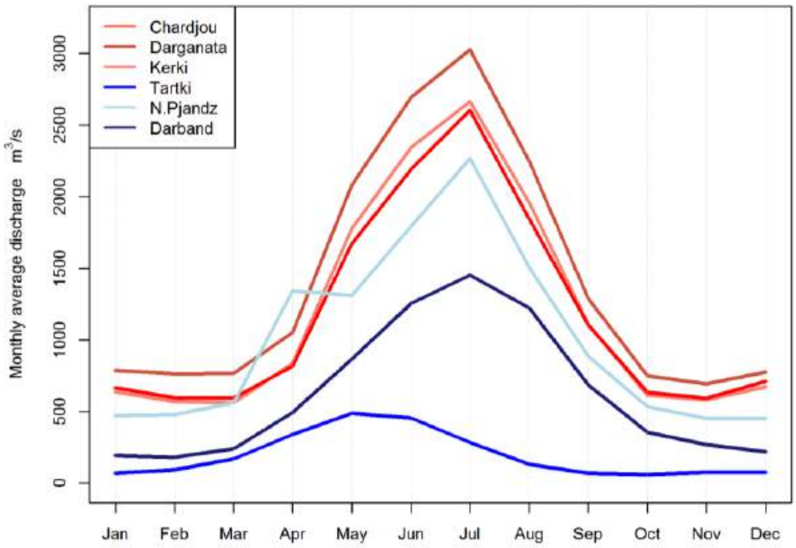

Figure 2 Long-term mean annual discharge, averaged over 1990-2015, at the gauging stations in the Amu Darya River Basins

In general, the water resources of the Amu Darya River are abundant. However, the rapid development of irrigational farming activities from 1960ies, large withdrawals (e.g. in the middle part nearly half of the river flow is diverted via the Karakum channel), construction of dams and reservoirs have led to significant depletion of water resources availability in the river and deterioration of water quality. The projected changes in climate will likely act as an additional stressor and will impose further challenges to water managers of the region. In fact, the current warming trends in the region show faster temperature increase than average global values, what also allows to suggest that the consequences of the climate change may have more pronounced effects in the region. E.g. Figure 3 and 4 present projections of temperature and precipitation for the Dashouz region, under RCP4.5 and RCP8.5. As one can observe from the figures, the projected changes in temperature show a strong increase, reaching up to plus six degrees until the end of the century under the high-end climate change scenario, while for the precipitation no clear trend can be observed. A strong increase in temperatures will likely affect the glacier mass balances and therefore also the Amu Darya River flow, which in turn may affect the chemical composition of the water altering the dilution and washing out processes.

In the view of projected changes, current state of the water resources of the Amu Darya River, as well as necessity for economic and social development in the region, the task of assessment of projected impacts of climate change on the water resources availability and water quality parameters becomes to be essential.

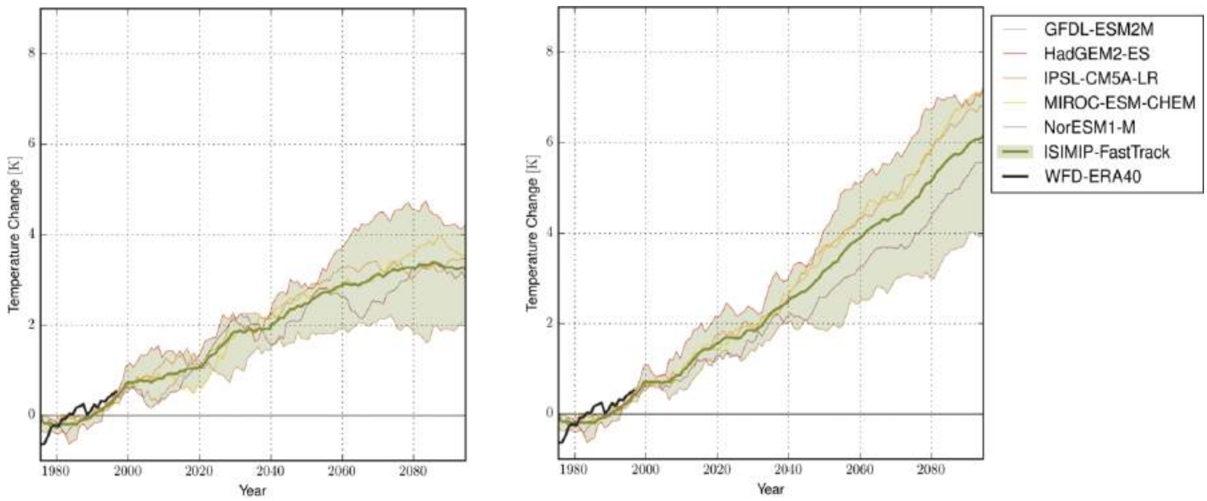

Figure 3. Anomalies in the average daily temperature in degrees K obtained as running means (10 years) with respect to 1971-2000 for Dashouz district under RCP4.5 and RCP8.5 scenarios; and anomalies for the WATCH ERA40 data until 2000 (Lobanova et al. 2017)

The aim of this consultancy task are 1) to investigate, how the water quality parameters in Amu Darya River are changing along the course of the river; 2) estimate the links between the discharge and water quality parameters; 3) provide an assessment, qualitative and, where possible, quantitative of how the projected changes in discharge under climate change scenarios RCP4.5 and RCP8.5 may influence the water quality parameters in the river basin. This report provides an overview of the water quality parameters dynamics in the Amu Darya River at the present moment and investigates the links between the discharge and selected water quality parameters.

For this analysis the datasets of the water quality parameters at seven observational stations, in Tajikistan, Turkmenistan, and Uzbekistan were received: Tartki (Kafirnigan River), Darband (Vahsh River), Kizyl Kala (Vahsh River), Karatag (tributary of Surkhandarya River), Kerki, Chardjou, Dargan-Ata (Amu Darya River). The measurements contained observations of mineralization, suspended matter, pH, NO_2, O_2, NH_4, NO_3, P, Ka from 1990 to 2015. The number of observations was varying significantly, depending on the station and parameter selected. An overview of number of observations per year for selected parameters at selected gauging stations is provided in Annex 1. The discharge and mineralization of main drainage channels in the lower part of the Amu Darya River and the mineralization of the effluent water were also provided with the monthly time step, covering a period from 1992 to 2015.

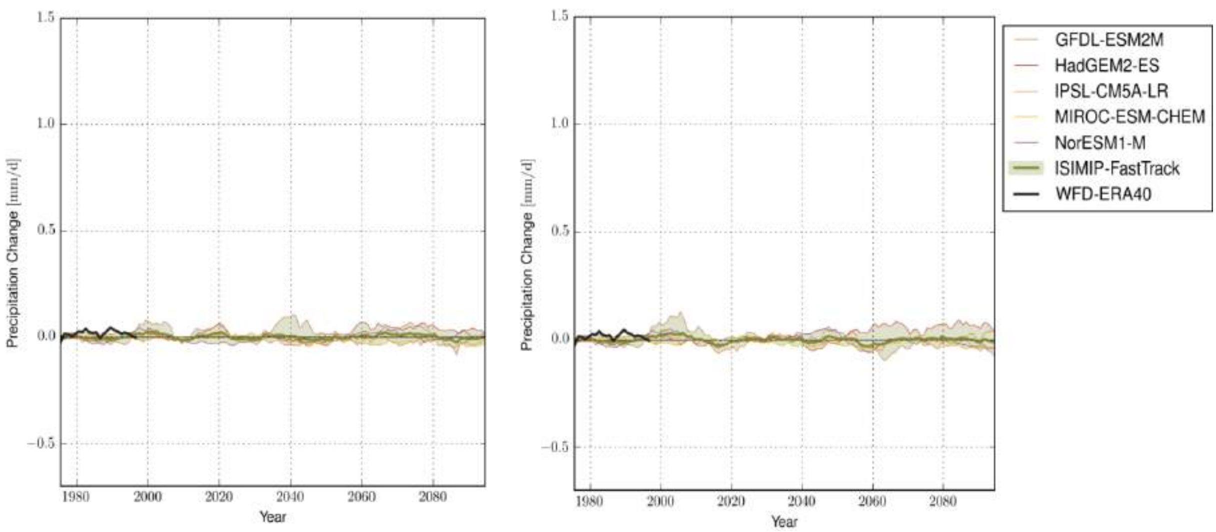

Figure 4 Anomalies in the average daily precipitation in mm obtained as running means (10 years) with respect to 1971-2000 for Dashouz district under RCP4.5 and RCP8.5 scenarios; and anomalies for the WATCH ERA40 data until 2000 (Lobanova et al. 2017)

The discharge and water quality parameters were measured simultaneously only at five of the provided stations: Tartki, Darband, Kerki, Chardjou, Darganata, therefore the current analysis is focused on these five gauging stations.

Firstly, in order to perform this study, it was intended to set-up an eco-hydrological model SWIM (Krysanova, Müller-Wohlfeil, and Becker 1998) for the entire Amu Darya River basin to conduct a process-based analysis of the water quality parameters. However, such modelling exercise, apart from the data needed for a hydrological model set up, requires a lot of additional input water quality data, of high quality, in order to reach adequate model performance for the water quality parameters. To perform a thorough calibration of the model, bi-weekly measurements of the water quality parameters are needed, with exact dates when each specific measurement was conducted. Further, daily discharge is needed in order to link the measurements of water quality with river discharge. Third, all information about the diffuse (e.g. effluent from agricultural fields) and point (untreated domestic, industrial or animal farms waste water etc.) pollution sources have to be provided, in order to be included in the model set-up. The received datasets contained observations, performed once per month (in the best case) with missing date of observation, the information on the point and diffuse sources of pollution was also not available, as well as information on the type and amount of fertilizers used at the agricultural fields.

Therefore, it was decided to investigate the statistical link between the selected water quality parameters – mineralization, nitrates and phosphorous and the discharge at the selected gauging stations. The mineralization of the water is one of the main issues, associated with water quality in the Amu Darya and therefore it was selected for the analysis. The phosphorous and nitrates (originating, e.g. from sewage and agricultural fields) are two other common parameters, suitable for general estimation of the quality state of a water source.

As was mentioned before, the observations of the discharge in the five gauging stations were provided as mean monthly values, whereas the observations of the water quality parameters were performed on several days per year, without the specification of the calendar date of the measurement. It should be, therefore, noted, that in some cases it may be challenging, if at all possible, to find direct statistical links between the measured with daily time step values of water quality parameters and river discharge, provided with monthly timestep, even if they exist.

2 Water quality of Amu Darya River

It should be noted that information and data regarding the state of the water quality of the Amu Darya River is poorly covered in the international literature.

In Amu Darya and in general in Central Asia there is a growing abstraction of water resources for industrial and household needs and, sequentially, increased discharges of polluted return flows into water bodies. In general, the water quality in the Amu Darya River is influenced by, in the first place, agricultural activities, followed by discharges of the untreated return flows from industry, domestic wastewater, mining and animal farms (SIC ICWC 2011).

As was mentioned before, one of the major challenges is the increase of mineralization of the water in the downstream part of the river basin. The current levels of mineralization at some stations limit the use of water for water supply and agriculture (Crosa et al. 2006). The major salt contributors to the river flow are the effluents from the drainage collectors, which collect water after irrigation and washing of saline soils. Currently, the total water withdrawal from the Amudarya river is 61 km^3, of which about 41 km^3 are used for irrigation. Besides, 15-18% of this withdrawn water is returned back into the river, i.e. 9-11 km^3/year. Figure 5 presents the increase in the mean monthly mineralization levels at selected gauging stations. One can observe that while in the Kafirnigan River basin the mineralization is not exceeding 400 mg/l, at the downstream parts, at Kerki, Chardjou and Darganata stations mineralization exceeds the 1000 mg/l level (palatability limit) in the spring months. The highest mineralization levels are recorded at the Kerki and Chardjou stations.

From Figure 5 one can also observe that the relationship of mineralization levels and discharge is inverse, hence for all analysed locations, the minimum values for mineralization occurring during summer (July and August) when the discharge of the river reaches its maximum, and maximum mineralization values occur in March and April, during the low flow period (see Figure 2).

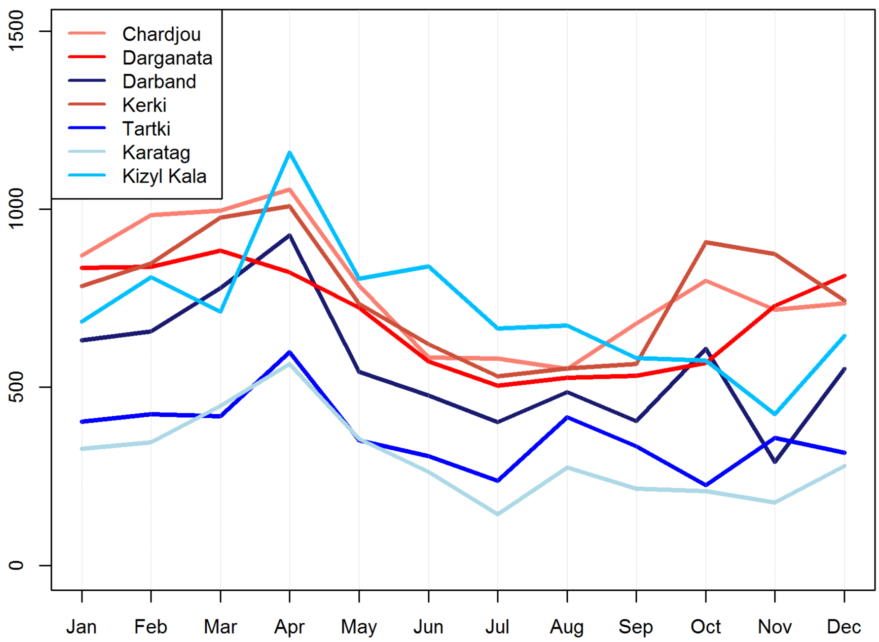

Figure 5 Mean monthly mineralization levels in mg/l at the selected gauging stations over 1990-2015 years

The scheme of diverting and returning water back to the river has emerged in 1960ies as a measure to save water resources, however the natural limits of water availability for dilution of saline effluents were not considered. Between 1960 and 1989 the average mineralization of the Amu Darya River has increased from 540 mg/l to more than 1000 mg/l (Crosa et al. 2006). Nowadays, more than 50% of the observations between 1996-2001 exceed the value of 1000 mg/l, which is considered as the limit of palatability (Crosa et al. 2006). Figure 6 presents yearly mean mineralization levels at the selected gauges. It is clear from the figure that before the 1998 the observations for all stations are characterized by scarce data availability. The years 2000 and 2001 are characterized by peaks in the mineralization levels, especially at the downstream gauges. This period there were drought conditions and the dilution processes were hampered. From the graph one can see that in recent years there is a slight upward trend in the mineralization levels in the downstream gauges and strong in the Kizyl Kala station and Darband stations (Vahsh River basin) as well as downward in Tartki and Karatag stations (Kafirnigan and Surkhandarya Rivers).

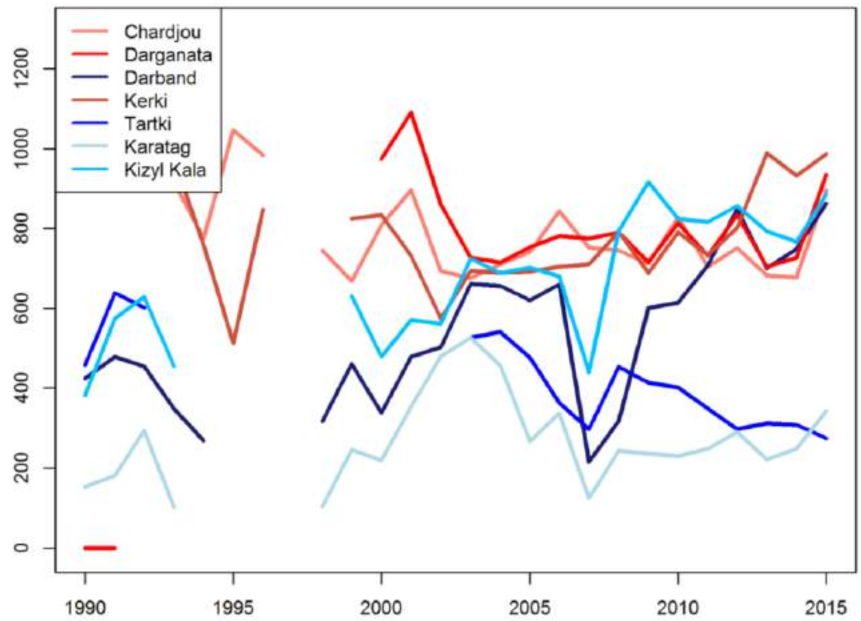

Figure 6 Mean annual mineralization levels in mg/l at the selected gauges

Though naturally the soils in the Amu Darya catchment are saline, the natural runoff processes are the minor contributor to salt effluents, due to low precipitation intensity in the catchment. The water quality at one of the downstream sections of Amu Darya at the Samanbay gauging station exhibit exceedance of maximum levels nearly for all important parameters, including mineralization, nitrates and phosphates (Crosa et al. 2006).

The main tributaries of the Amu Darya River are rivers Vahsh, Surkhandarya, Kafirnigan and Pianj. The former tributaries Zeravshan and Kaskadarya are not reaching the main stream of the Amu Darya, as all water resources of both rivers are diverted to the agricultural fields (SIC ICWC 2011).

The lowest water quality is observed in the **Surkhandarya River**, due to untreated effluents of the industrial and municipal waste water, as well as agricultural chemicals along its entire length. The water quality of the **Zeravshan River** is mainly impacted by the mining and polluted by heavy metals. In the **Kafirnigan River** basin, as well as in **Pianj River** Basins there are agricultural collector drains, but the soils are in general low saline and the mean annual mineralization of water discharged into the reach is 350 to 700 mg/l for Kafirnigan and up to 1000 mg/l for Pianj River. The soils in the Vahsh River catchment are more saline than in the Kafirnigan and Pianj River catchments and there are about 20 collector drains, serving irrigated area (SIC ICWC 2011).

Apart from Surkhandarya the contribution of the untreated urban and industrial wastewaters to the overall level of pollution can be considered minor, as compared to the pollution with agrochemicals.

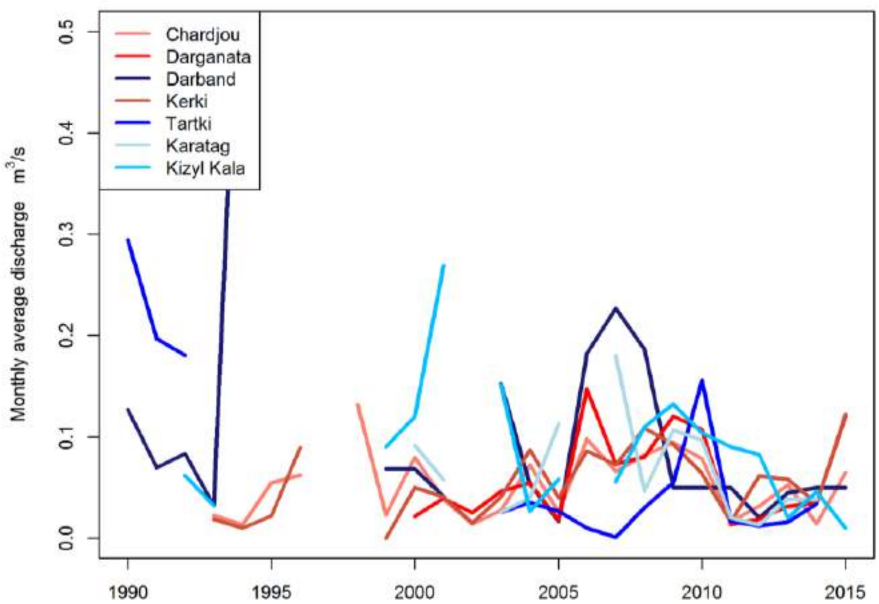

Figure 7 Mean annual phosphorous levels in mg/l at the selected gauges

Figure 7 depicts mean annual levels of phosphorous at the selected gauges. One can observe the scarcity of observations before the year 2003 in all gauging stations. The levels of phosphorous show no growing trend in the longitudinal profile and seem to depend rather on the point source pollution in each particular case.

Figure 8 presents the nitrates levels at the selected gauges with yearly time step. The nitrates levels are lowering when moving from upstream to downstream, possibly due to the dilution processes, showing the maximum values in the upstream parts of the Amu Darya River Basin, until the year 2010, after that the measurements are indicating growing trend in nitrates levels.

Chardjou, Dashouz, and Khorezm oases are located further downstream of the Amudarya river. Collector drains located in the first two oases have water mineralization varying from 1300 to 3500 mg/l, while their discharge is from 1.3 to 45 m^3/s. Between the Kerki and Darganata gauges the Amu Darya River receives approximately 40% of all return water.

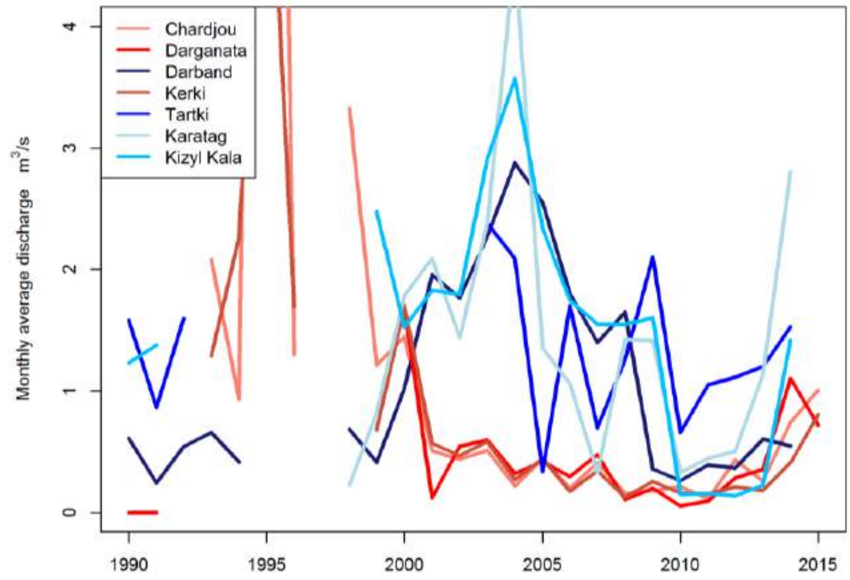

Figure 9 Mean annual nitrates levels at the selected gauges

The estimated mean discharge from main drainage outlets to the Amu Darya River between the Termez and Samanbay gauges is approximately 140 m3/s (based on the received datasets with records of drainage discharge over 1992 -2015).

Figure 10 presents the sum monthly discharge for the 20 selected (according to data availability, mainly in the downstream parts, between the Kelif and Darganata gauges) drainage channels, over the period of 1992-2015 and their average mineralization based on the received datasets with observations. One can observed that, there are growing trends in terms of water volumes, discharged back into the Amu Darya, as well as in their average mineralization.

Figure 11 depicts the mean monthly discharge of the drainage effluents into the Amu Darya River, based on the received data, as well as average mineralization of those. One can observe that the drainage discharge reaches its maximum from March until August and the mineralization of flows is slightly higher in the spring months – March April.

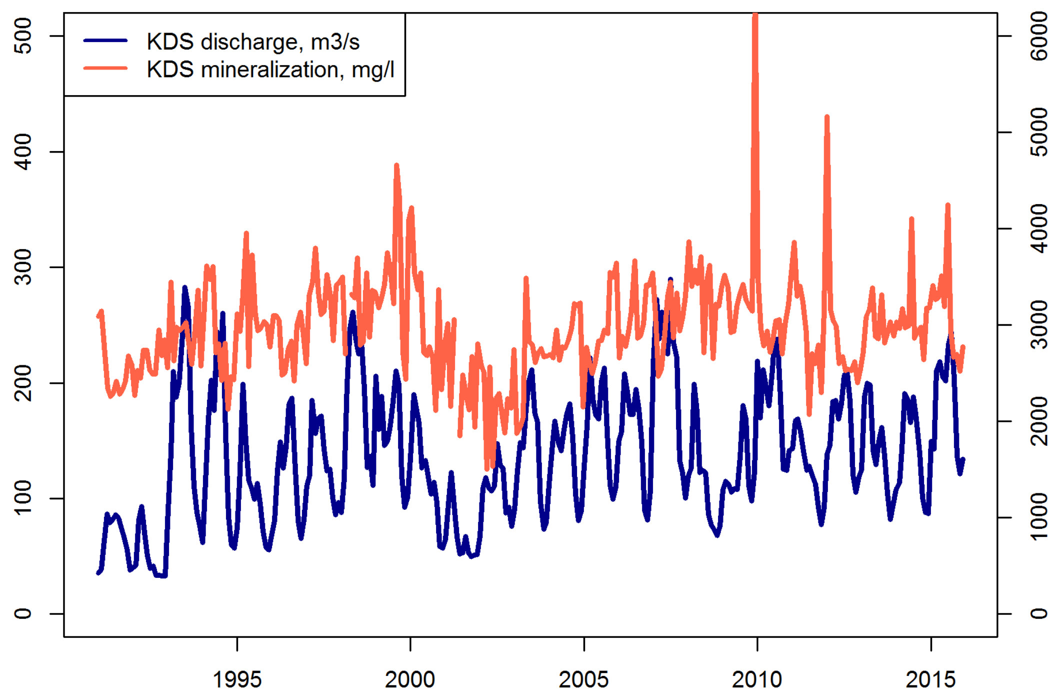

Figure 10 Sum of all monthly discharge of drainage water into Amu Darya River and its average mineralization based on selected drainage channels over 1992-2015

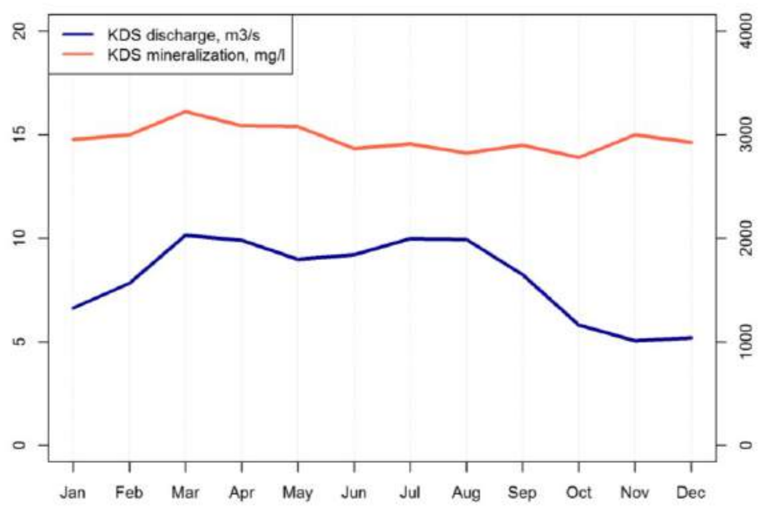

Figure 11 Mean monthly discharge and mean mineralization of return flows into the Amu Darya River over 1992-2015

3 Water quality parameters – flow relationships

3.1 Mineralization-discharge relationship found in the literature

Crosa et al. (2006) conducted an analysis of the relationship between mineralization and river discharge for the Kerki and Darganata gauging stations. The data were supplied with the monthly timestep and covered the period of 1996 to 2001.

They conducted, that the Amu Darya is a system where mineralization responds strongly to the variations of discharge. Further, there are two major factors influencing the mineralization levels in the river reach, firstly the high flows that are diluting the drainage effluents and decreasing the mineralization of water and second, the influence of low flows which are occurring in spring months – March –April, when also the leaching from the drainage system is slightly higher due to soil washing.

Based on their analysis of observed data, both discharge and mineralization recorded with monthly timestep, they suggest the following model to describe the mineralization-discharge relationship for the Kerki and Darganata gauging stations (graphical representation on Figure 12):

$$C_i = a \cdot Q_i^b$$

Where c – concentration of dissolved compound, Q_i – discharge, a – dilution effect, b – basal flow

The estimated values of the coefficients for the Kerki station are: a = 6664.08, b = 0.34, and for the Darganata station are: a = 11032.91, b = -0.34.

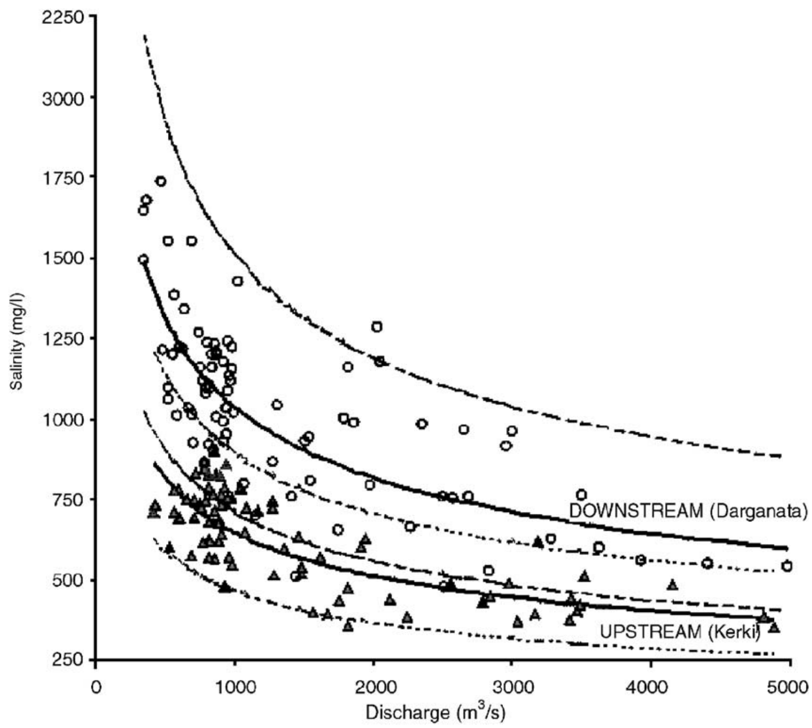

Figure 12 Mineralization and discharge relationship at Kerki and Darganata gauging stations. (Crosa et al. 2006)

3.2 Estimated from the observed data received

Based on the received observed data, described in Chapter 1 the following graphs, representing the mean annual discharge values against the three selected water quality parameters: mineralization, phosphorous and nitrates are presented for each selected gauge – Figures 13 to 17.

3.2.1 Tartki

For the Tartki station, located at the Kafirnigan River basin from Figure 9 it can be seen that there is a positive correlation between the levels of nitrates that are growing together with the increasing of the flows in spring, levelling off during the summer months and then decreasing in winter and autumn. For the mineralization the picture is slightly different than for the other gauges – the increased level of mineralization in spring months – April, when possibly the washing of the soils is happening is diluted by the peak flow in May, reducing the levels dramatically, then in summer the mineralization levels are levelling off. No direct correlation between the discharge and mineralization levels can be observed, although the visual inspection of the graphs suggests an inverse relationship between those. For the phosphorous no clear correlation can be found with the discharge. From Figure 9 one can observe increase in the phosphorous levels during the low flows and decrease during the high flows.

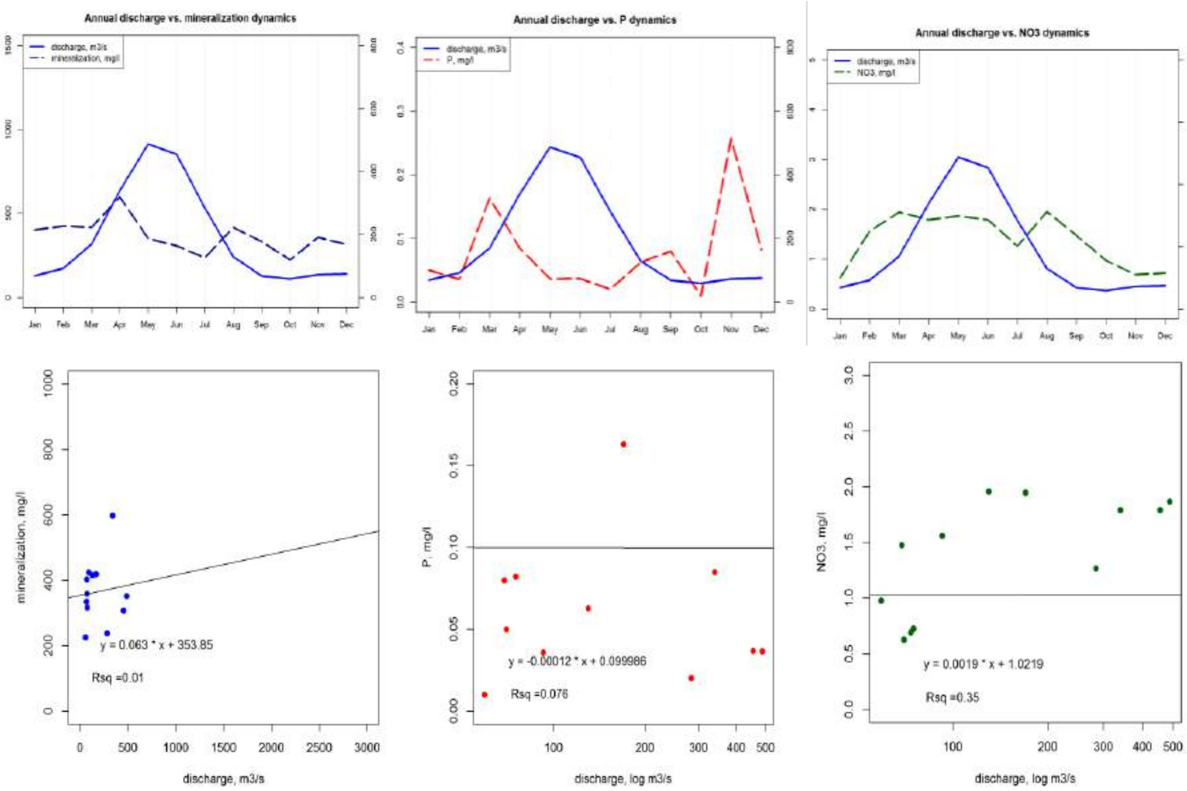

Figure 13 Average annual discharge vs mineralization, phosphorous and nitrates dynamics and their correlations for the Tartki gauging station

The levels of the phosphorous are also relatively high in November, which allow to suggest some point pollution source, e.g. outlet of untreated waste water or similar.

3.2.2 Darband (Komsomolabad)

The relationship between the discharge and water quality parameters for the Darband station is similar to the one described for the Tartki, in particular, inverse relationship between the levels of mineralization and phosphorous with the discharge rates and direct relationship between the nitrates levels and discharge. Also for Darband station there are peak in the phosphorous levels in November, indicating probable point source pollution, as for Tartki station.

Similarly, weak inverse correlation between the mineralization and discharge was found, but from the graph with mean annual discharge and mineralization levels it is clear that there should be a stronger inverse relationship.

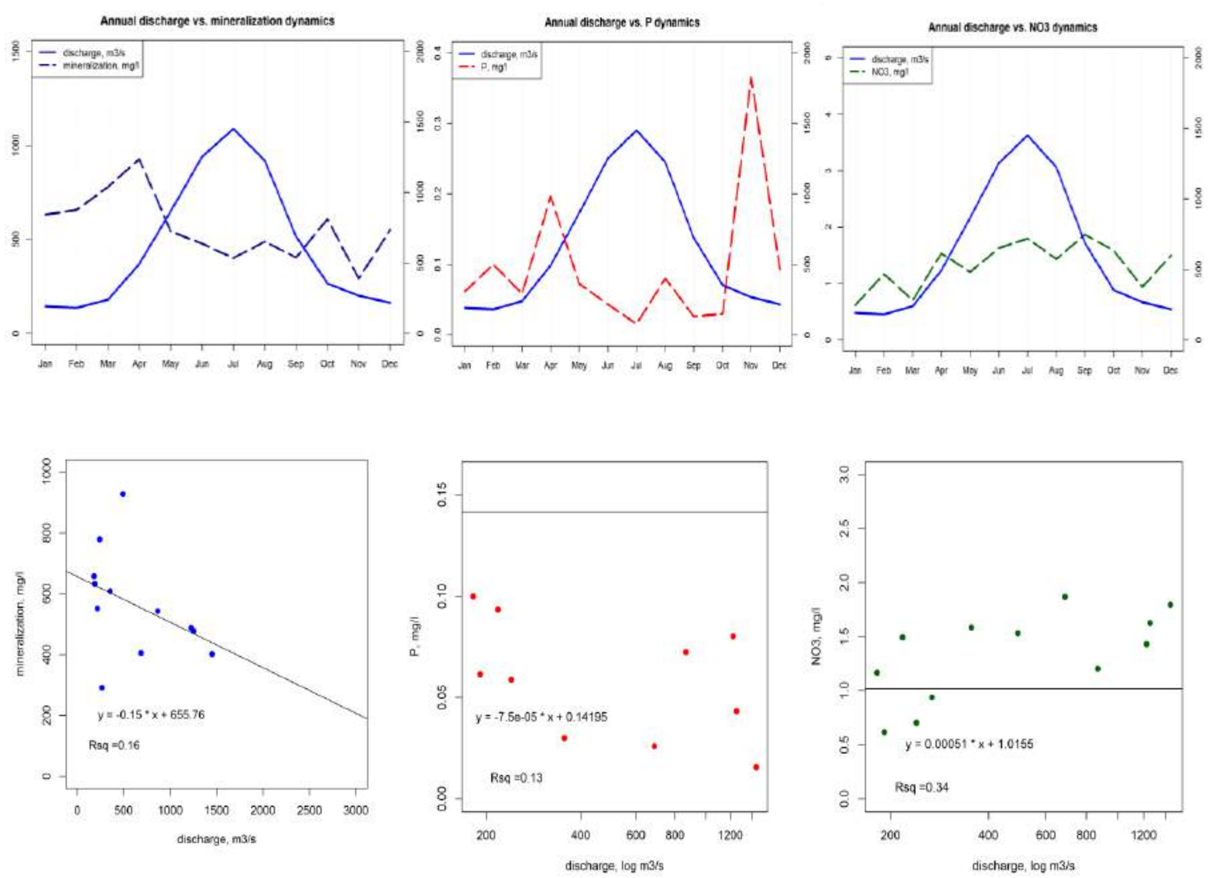

Figure 14 Average annual discharge vs mineralization, phosphorous and nitrates dynamics and their correlations for the Darband gauging station

3.2.3 Kerki

For the Kerki station, the correlation between the mineralization levels and the discharge becomes to be stronger, resulting in R^2=0.57. At the same time there is no clear correlation between the phosphorous and nitrogen levels as for the upstream gauges. The phosphorous levels at this station also show relatively stable levels throughout the year and are lower, than in the upstream gauges, possibly also due to dilution processes and less pollution load.

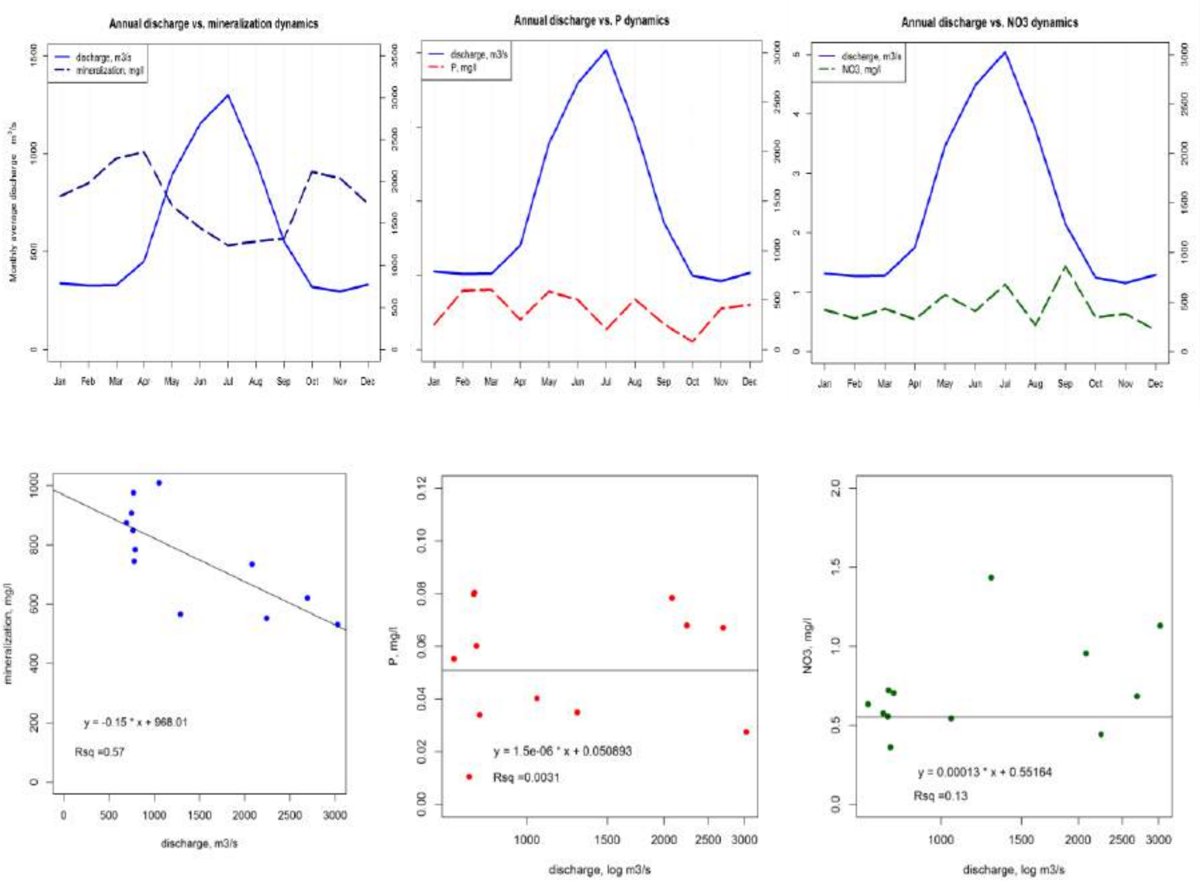

Figure 15 Average annual discharge vs mineralization, phosphorous and nitrates dynamics and their correlations for the Kerki gauging station

3.2.4 Chardjou

The relationship between the mineralization and discharge is also strong for this gauging station. The levels of phosphorous are also relatively stable throughout the year. However, there were two observations in the time series of phosphorous of 6.68 and 13 mg per litre, which probably indicate single untreated waste water discharges or an erroneous observation. Those were excluded from the analysis as outliers.

The nitrates show some peaks in spring months, what probably can indicate the agrochemical pollution originating from the fertilizers, which are applied in the agricultural fields and then washed out during the soil washing in spring months.

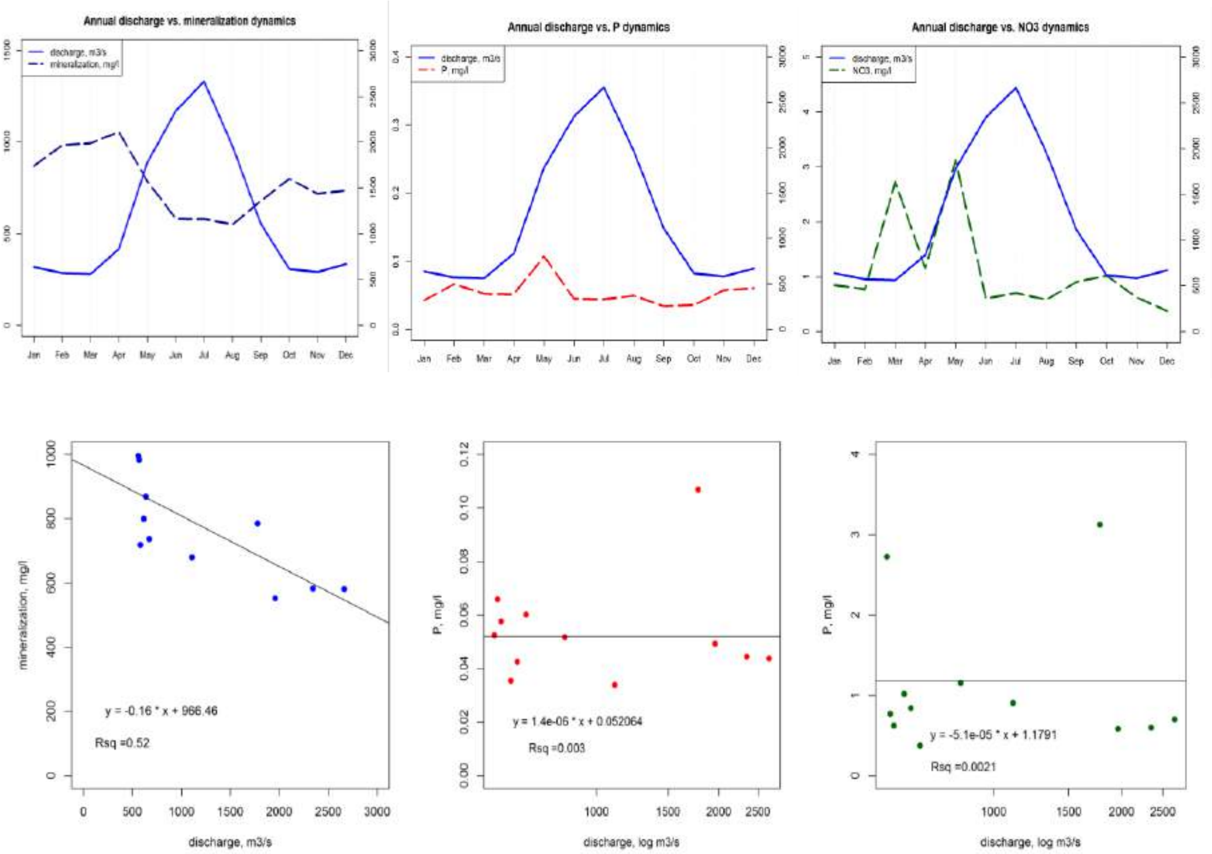

Figure 16 Average annual discharge vs mineralization, phosphorous and nitrates dynamics and their correlations for the Chardjou gauging station

3.2.5 Darganata

For the Darganata the picture is similar as for the Kerki and Chardjou gauges – strong correlation of mineralization to discharge levels, relatively stable levels of nitrates and phosphorous throughout the year.

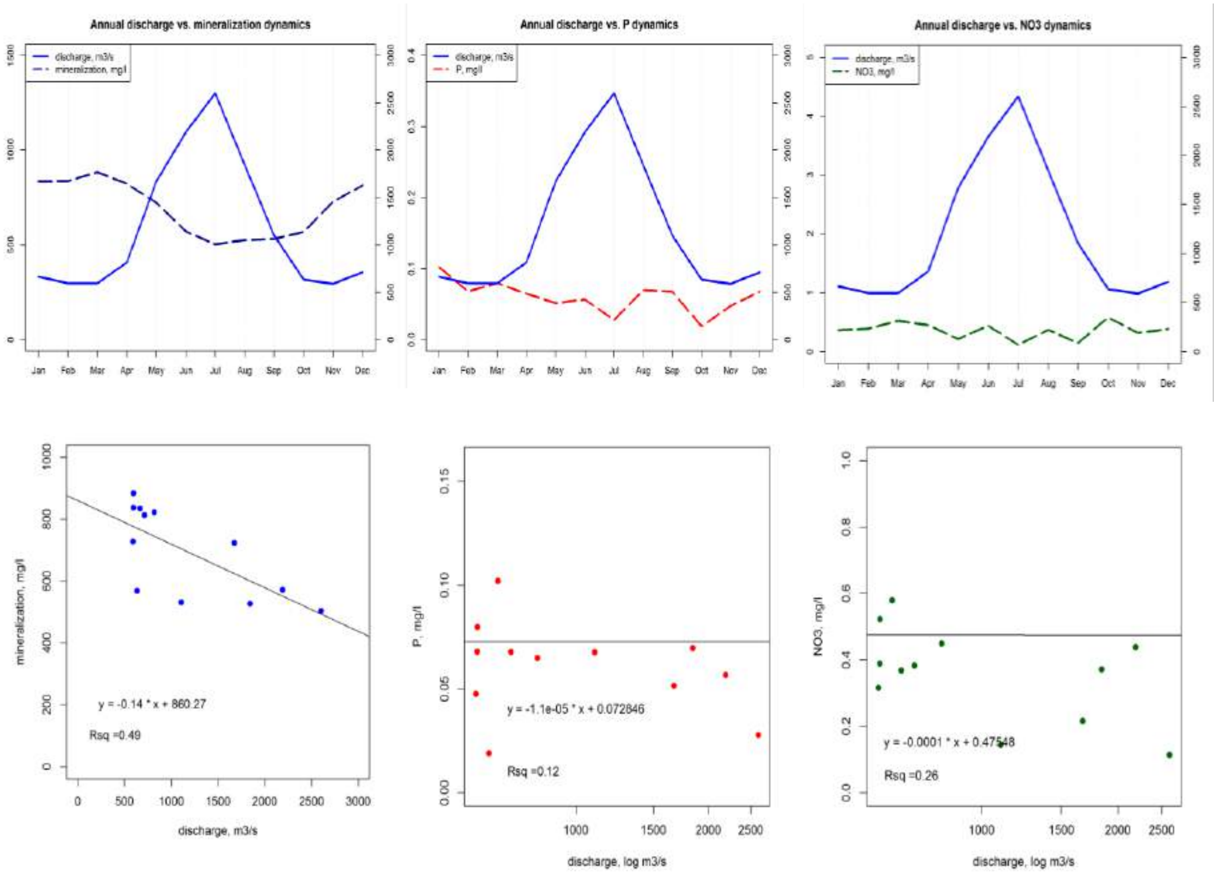

Figure 17 Average annual discharge vs mineralization, phosphorous and nitrates dynamics and their correlations for the Darganata gauging station

4 Hydrological Modelling of the Amu Darya

The hydrological modelling of the Amu Darya River was focusing on the upstream zone where the majority of the water resources are formed, as downstream the Amu Darya receives nearly no rainfall. Additionally, the river experiences strong anthropogenic influence, e.g. water storages, water transfers etc. downstream of the Kelif gauging station challenging the modelling processes. It is possible to take into account the irrigation, water withdrawals and return flows within the setup of the eco-hydrological model SWIM, however it was not feasible to implement it due to limited time and observed data. Therefore, the eco-hydrological model SWIM was set up until the Kelif gauging station. The statistical correlation between the discharge at the Kelif station and the downstream Kerki, Chardjou and Darganata stations was estimated with the help of linear regression and applied to obtain the projections of the discharge in the future.

4.1 SWIM Model

The Soil and Water Integrated Model SWIM is a process-based deterministic eco-hydrological model for the river basin scale, developed based on two previously created models: SWAT and MATSALU, and described in Krysanova et al. (1998). The model allows representation of components of hydrological cycle and related processes at the river basin scale.

The SWIM model combines numerical representations of main physical processes of hydrological cycle and related processes (vegetation/crop growth, nutrient cycling, and erosion). These physical and geochemical processes are mathematically interpreted using physically-based and semi-empirical equations. The three main modules of the model are hydrological, biogeochemical and plant growth modules (schematically represented in Figure 18). The SWIM model operates on a daily time step and uses climatic, land use, topographic and soil datasets as input files. SWIM was successfully applied for climate and land use change impact studies in many mesoscale and large river basins in Europe, Africa, Asia and Latin America. Thanks to additional integrated modules, the model allows to integrate the water management infrastructure, e.g. reservoirs and dams, water transfers, irrigation processes and wetlands processes in one integrated modelling framework.

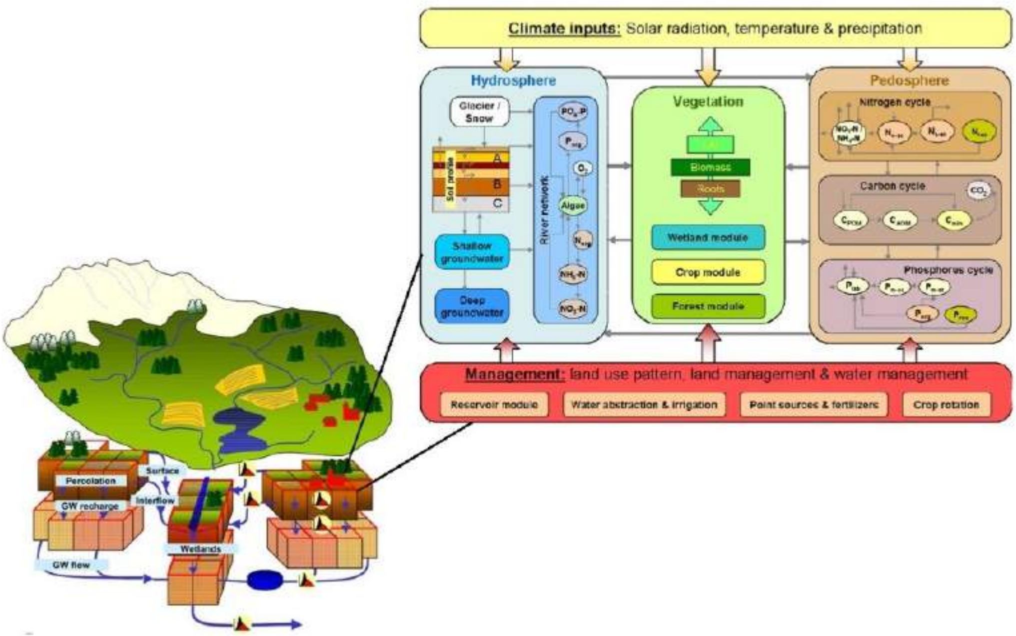

Figure 18 Schematic representation of the SWIM model components

4.2 Input Data

The following data covering the Amu Darya region, which are needed for the SWIM model set up and application, were retrieved from the global databases:

- The Digital Elevation Model (DEM) is available over the entire globe from the Shuttle Radar Topography Mission (SRTM) Consultative Group for International Agricultural Research (CGIAR) Database (Javis et al. 2008). This dataset is available on the CGIAR website[1]. It was initially produced by NASA, has a resolution of 90 x 90 m at the equator, and is provided as the 0.5 x 0.5 degree mosaic set.
- The soil information was obtained from the Harmonized World Soil Database FAO70 (HWSD, (Panagos et al. 2012)) created by the Food and Agriculture Organization of the United Nations is available over the entire globe. The missing in the database but required for the SWIM Model additional soil parameters were estimated using the method of pedotransfer functions.
- The land use data set was obtained from the GLC30 cover product, with the resolution of 30 m x 30m.
- The daily climatic data series of daily precipitation, average, minimum and maximum temperatures, solar radiation and relative humidity were obtained from the WATCH Era 40 reanalysis data set (Weedon et al. 2010)
- The discharge at the Kelif gauging station was obtained as a sum of water volumes diverted via the Karakum channel and discharge at the downstream gauge – Kerki. The data were obtained from the project partners Interstate Coordination Water Commission of the Central Asia (SIC ICWC).

4.3 Calibration and Validation Results

The spatial coverage of the setup SWIM Model is presented in Figure 19. Figure 20 presents the results of calibration and validation of the model to the observed discharge at the Kelif gauging station, performed with the monthly timestep.

The calibration period was from 1992 -2000 and the validation period from 1990-1999. The SWIM Model showed good representation of the observed discharge dynamics and resulted in the high values of the simulation efficiency criteria (Nash Sutcliff Efficiency of 0.78 and Relative Volume Error of 1% for calibration period and Nash Sutcliff Efficiency of 0.79 and Relative Volume Error of 1% for validation period). However, one can observe that the peak

[1] http://srtm.csi.cgiar.org/

simulated discharge is occurring approximately one month earlier when comparing to the observed one, introducing additional uncertainty to the results.

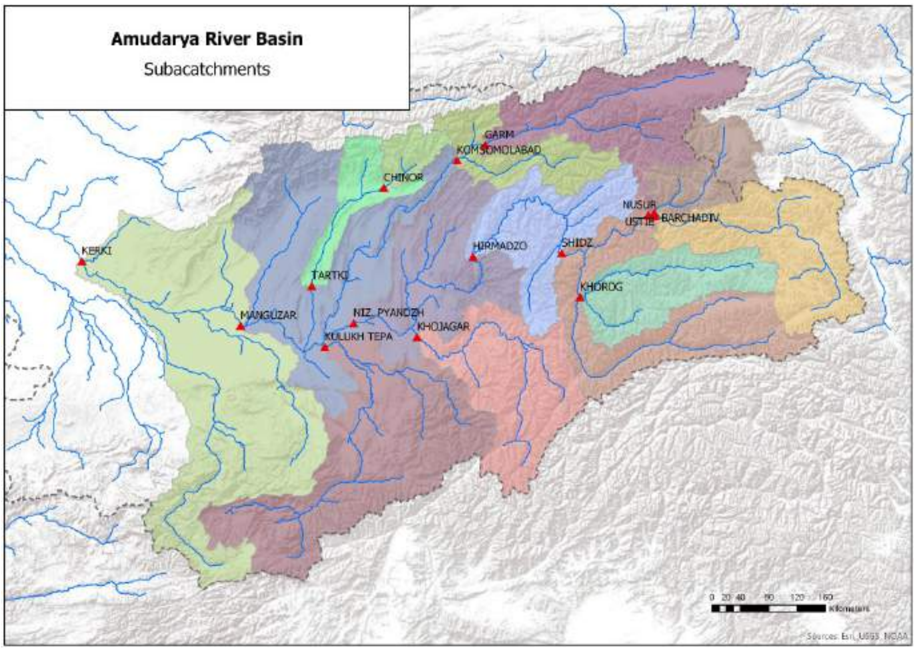

Figure 19 Spatial extent of the setup SWIM Model for the upstream part of the Amu Darya River Basin and respective sub catchments for the main gauging stations in the basin

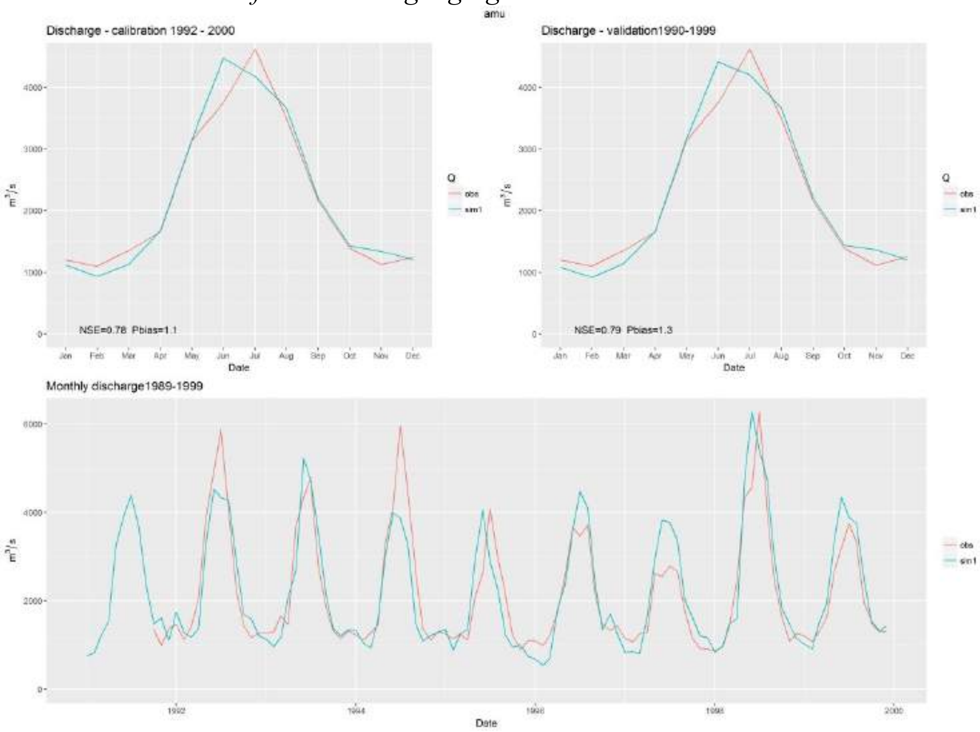

Figure 20 The calibration and validation results of the discharge at the Kelif gauging station simulated with SWIM Model against the observed values

5 Climate Change Scenarios

The climate change projections used to assess the impacts of climate change on the discharge were obtained from the Global Climate Models (GCMs) simulations within the CMIP5 (Climate Model Intercomparison Project, Phase 5) Project. In order to increase the coarse resolution (app. 300 km) of the GCMs outputs, they were statistically downscaled using a combination of bilinear remapping and bias-correction against a high resolution observation datasets WATCH ERA 40 within the ISI-MIP project (Hempel et al. 2013). Two contrasting climate change scenarios were selected to portray possible future development – the low-end, "utopic" global warming scenario RCP2.6 and extreme warming, high-end scenario of RCP8.5.

6 Climate Change Impact on discharge and water quality parameters

6.1 Discharge

In Annex II presented Figures A4 to A11 depict mean annual discharge at the selected gauging stations. As one can observe, under the low warming climate change scenario RCP2.6 no trends in the annual average discharge was observed at any of the considered gauges – Tartki (Kafirnigan), Kizyl Kala (Vahsh), Nizhniy Pianj (Pianj) and Kelif (Amu Darya) until the end of the century. On the contrary, under the RCP8.5 only the Kafirnigan River exhibit no trends in annual mean discharge, whereas in other gauging stations slight decrease in the discharge, when reaching the end of the century can be observed.

Further, as can be seen on the Figures A12 to A19 in Annex II under the RCP2.6 scenario shifts in inter-annual flow distribution are expected – at all selected gauging stations the maximum discharge currently appearing in spring and early summer is expected to be shifted to an earlier period, what will result in increase in early summer and late spring discharge by maximum 20%. At the same time, in late summer and autumn the flows are expected to decrease, also by maximum 20%.

When looking at the extreme global warming scenario – RCP8.5 (Figures A20 to A27 in Annex II) one can observe similar trends in the impacts, but more pronounced – shift of maximum discharge to an earlier date (one month by the end of the century) and strong decrease of flow during late summer and early autumn months (already by mid-century), reaching up to -50%.

6.2 Water quality parameters

As the SWIM Model was set up only for the upstream part of the Amu Darya catchment, until the gauge Kelif and in order to apply the regression formula, derived in Chapter 3 of this report, the discharge at the gauges Kerki, Chardjou and Darganata was estimated using the statistical relationship between the discharges at those gauges and Kelif gauge, estimated from observations.

Since not for all selected water quality parameters it was possible to derive the strong statistical correlation, some of those were decided not to be taken into account. Further, the quantitative analysis of selected water quality parameters will be presented as relative deviation in values in the respective future period to the baseline (1981-2010), expressed in percentage. The results of the analysis are presented only until the year 2070, as it was based on the statistical relationship, which likely be altered in the future, triggered by natural and anthropogenic changes in the system.

6.2.1 Tartki

For the Tartki gauge only the relative changes in nitrates levels were considered and are presented in Figure 21 and 22.

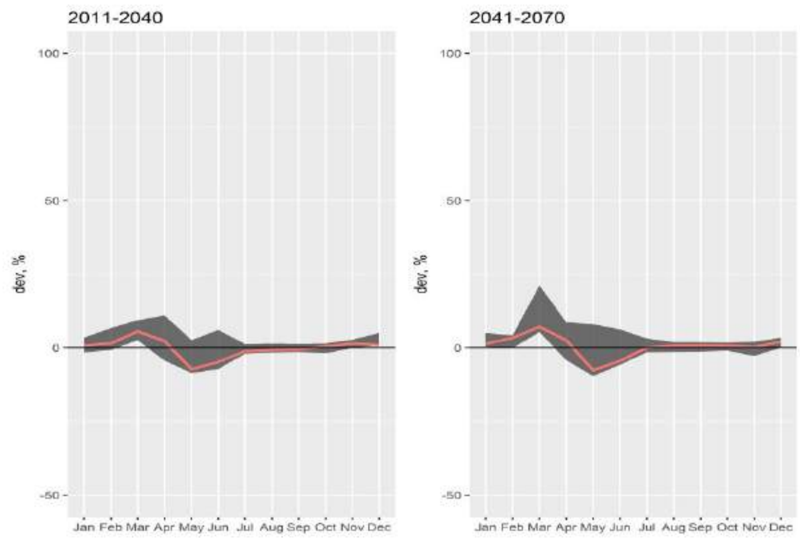

Figure 21 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Tartki gauge

As one can observe, the levels of nitrates are expected to slightly increase in March and decrease in late spring and early summer under both climate change scenarios and for both future time slices. As was discussed above, there is a positive correlation between the nitrates levels and the discharge, what can be also observed here – the shift of discharge peak to an earlier date also drives the shift of nitrates peak concentration to an earlier date.

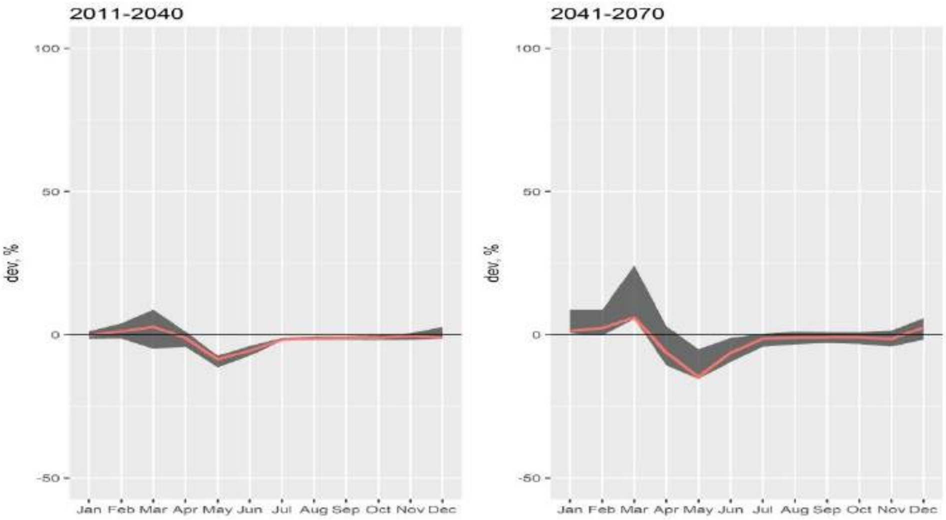

Figure 22 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Tartki gauge

6.2.2 Darband

For the Darband gauging station the levels of mineralization and nitrates were considered, results are presented in Figures 23 – 26.

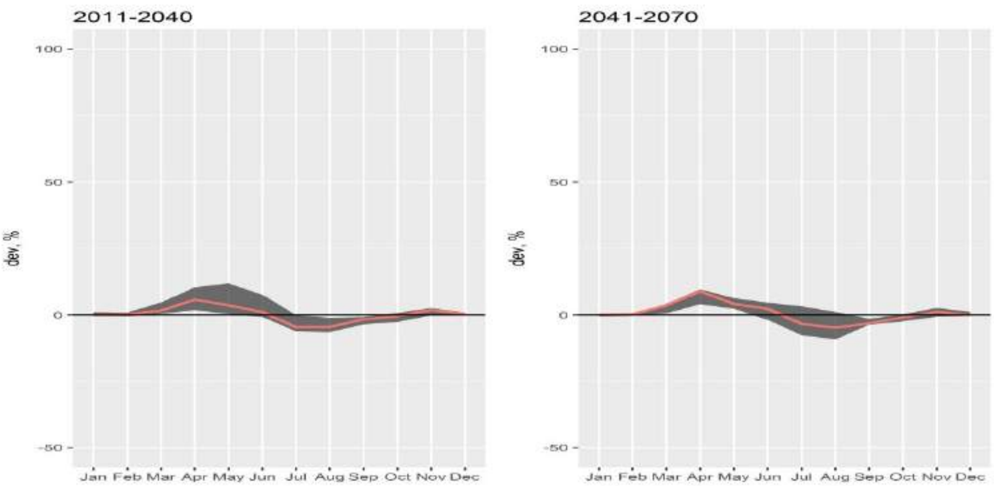

Figure 23 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Darband gauge

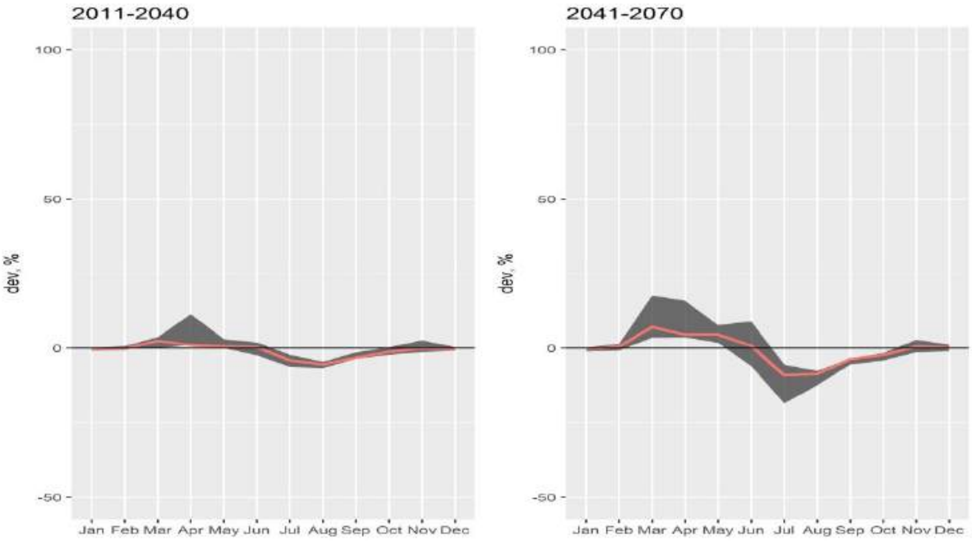

Figure 24 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Darband gauge

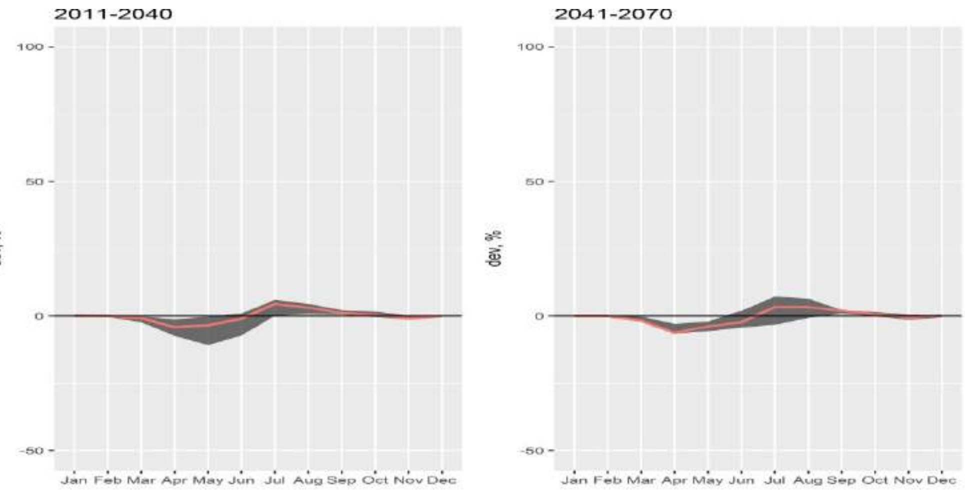

Figure 25 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Darband gauge

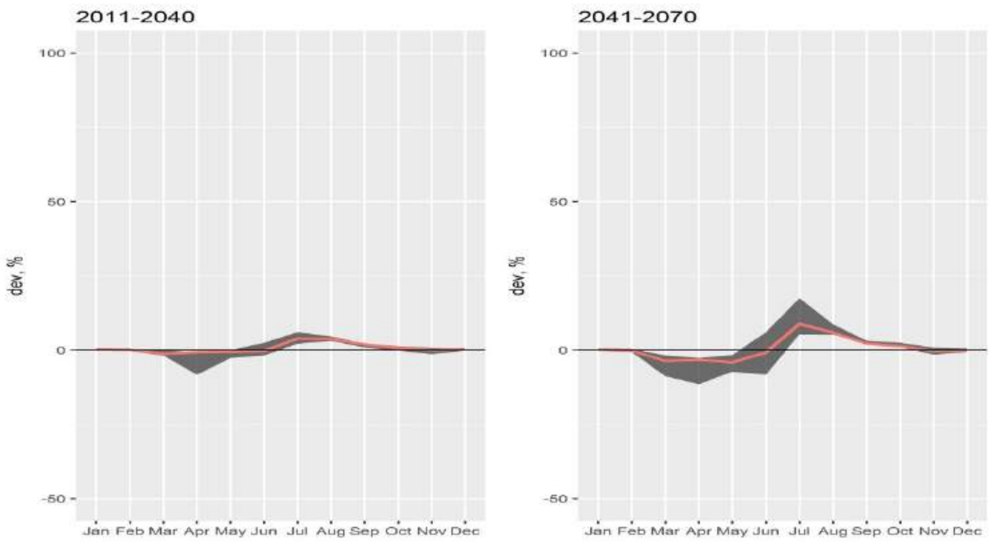

Figure 26 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Darband gauge

The projections at this gauging station have similar trends as for the Tartki gauge – the levels of nitrates are expected to follow the changes in the discharge levels, resulting in slight increase in April, May and June and decrease during summer and early autumn months. On the contrary, the mineralization levels have different dynamics – showing decrease in concentration during the spring and early summer months and increase in summer and early autumn months. One also should note, while treating the percentage values with caution, the projected changes are less than 10% for all future periods under RCP2.6 and under RCP8.5 become higher than +-10% only for intermediate future period – until the year 2071.

6.2.3 Kerki

For the Kerki station Figures 27 and 28 present the projected levels in mineralization using the relationship, estimated by Crosa et al. (2006). Figures 29 and 30 present the estimated levels in mineralization, derived from observations supplied by the local partners.

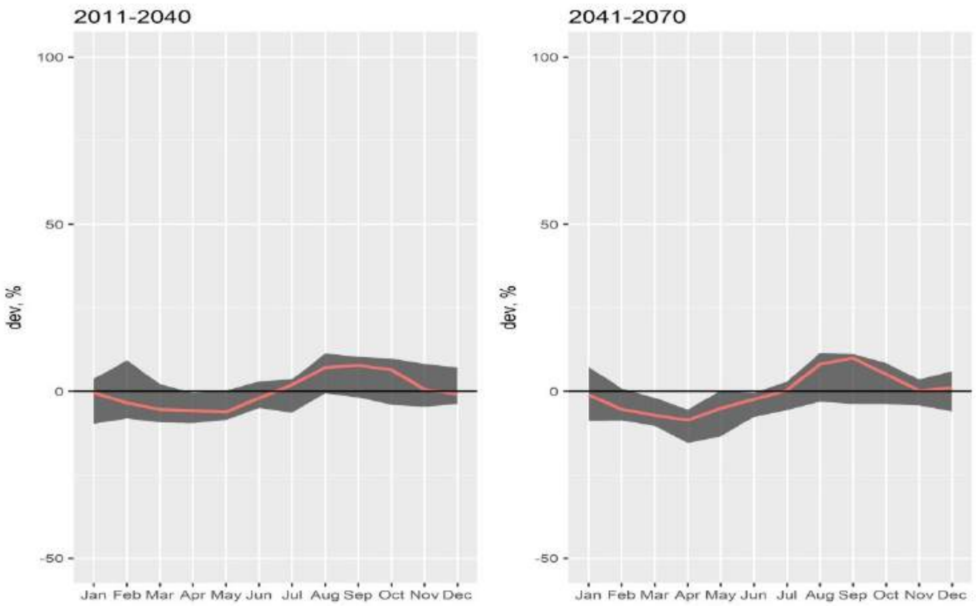

Figure 27 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Kerki gauge (estimated after Crosa et al. 2006)

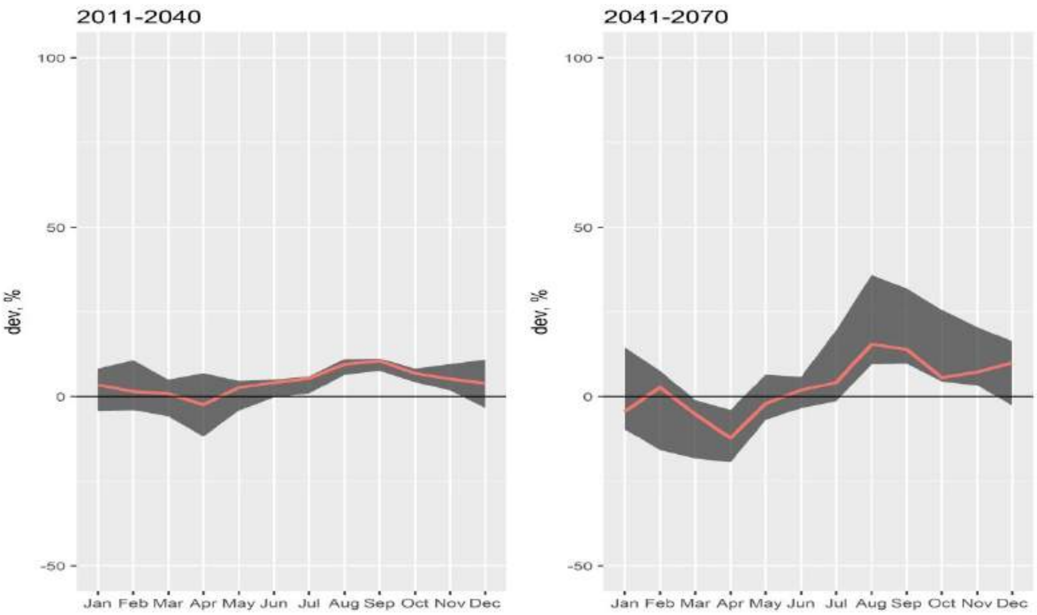

Figure 27 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Kerki gauge (estimated after Crosa et al. 2006)

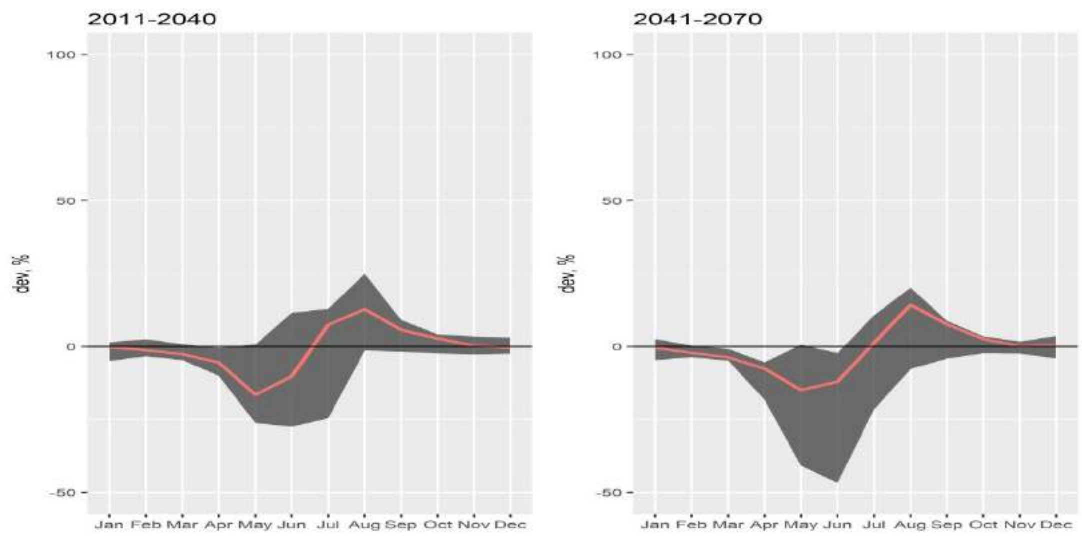

Figure 28 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Kerki gauge (own elaboration)

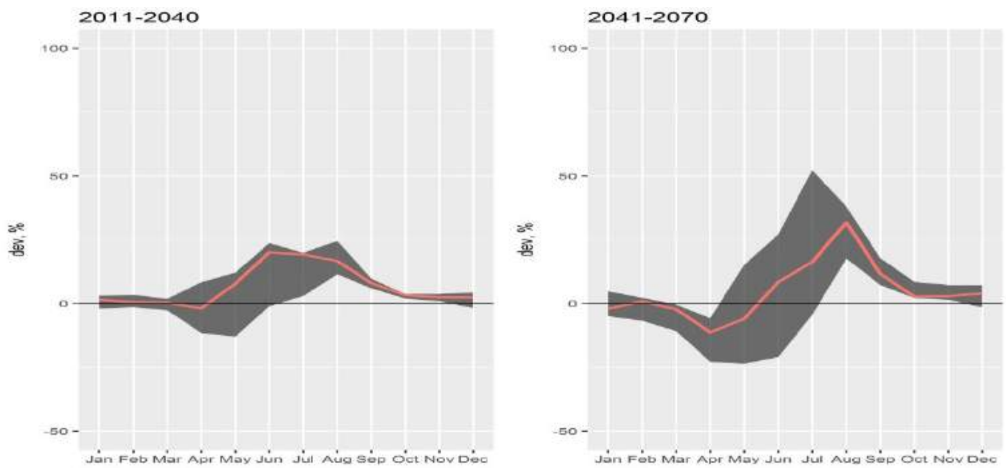

Figure 29 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Kerki gauge (own elaboration)

For the Kerki gauge, stronger changes in the mineralization levels are projected, than for the upstream gauges. Under climate change the decrease in the mineralization levels is projected in the March and April under both climate change scenarios and both future period and using both statistical relationships. The statistical relationship derived from data, received from the project partners, show stronger increase in the mineralization for the intermediate future period under the high-end scenario, reaching increase by 30%.

6.2.4 Chardjou

Figures 30 and 31 present relative changes in the mineralization levels for the Chardjou gauging station for the two climate change scenarios.

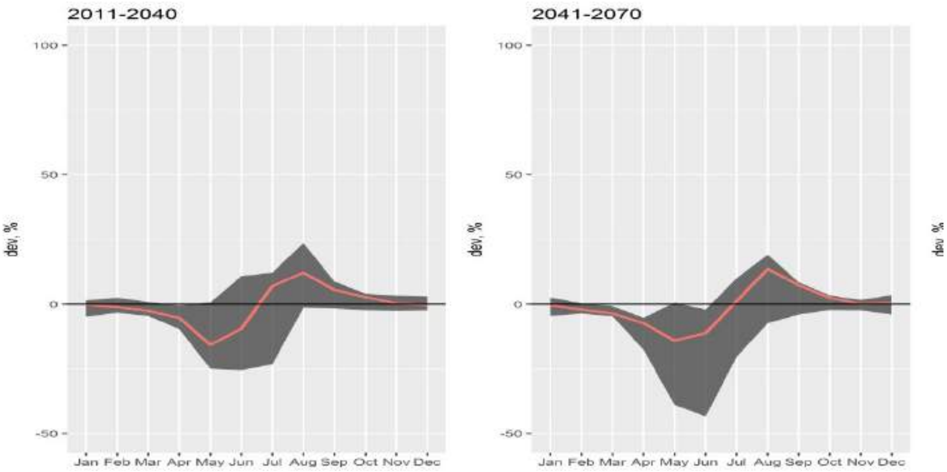

Figure 30 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Chardjou gauge

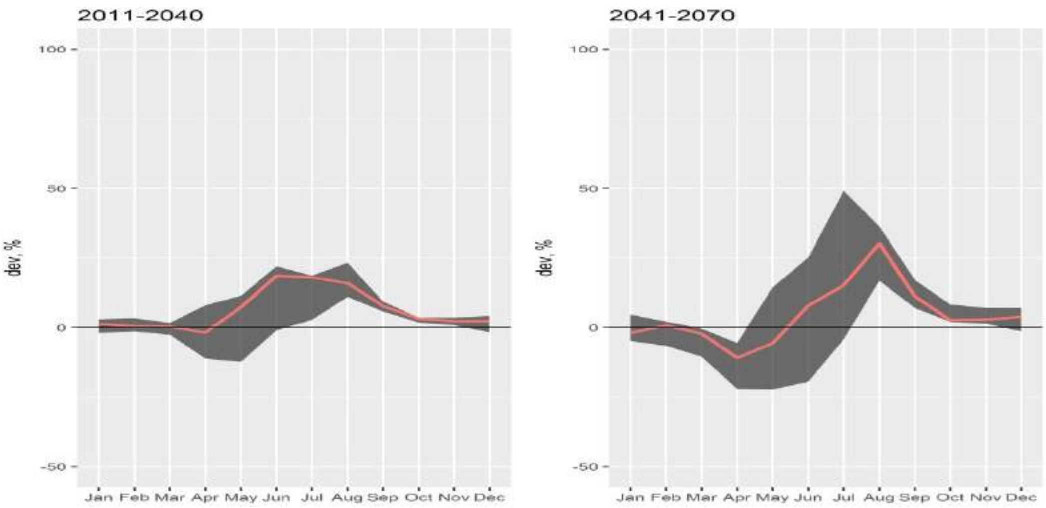

Figure 31 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Chardjou gauge

The mineralization levels are projected to increase in summer and slightly decrease in spring, reaching up to +33% for intermediate future period under the high-end climate change scenario. Under the low end climate change scenario the changes in the mineralization levels are expected to reach up to + 20% percent, as indicated by the multi-model mean.

6.2.5 Darganata

Figures 32 and 33 present the mineralization levels at the Darganata gauging station, estimated using the statistical relationship, described by Crosa et al. (2006) and Figures 34 and 35 changes in levels of mineralization based on own elaborated dependencies.

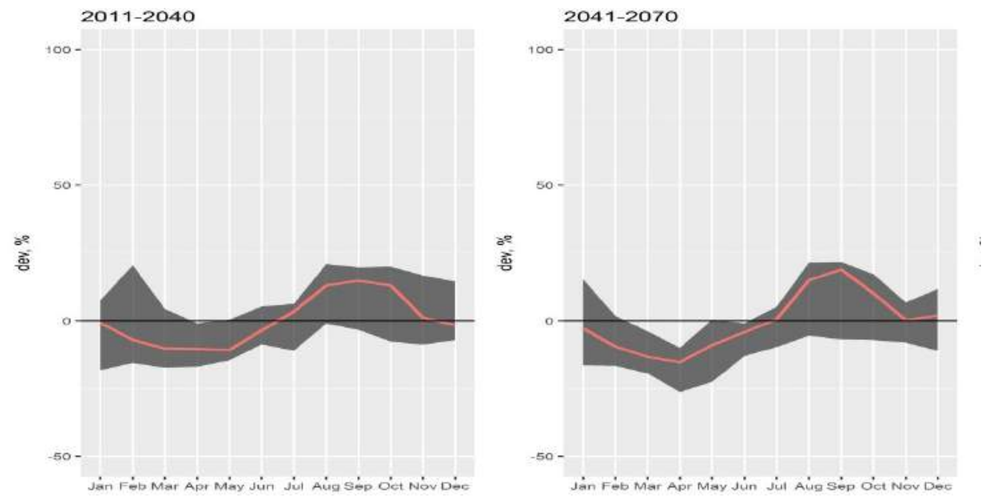

Figure 32 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Darganata gauge (after Crosa et al. (2006))

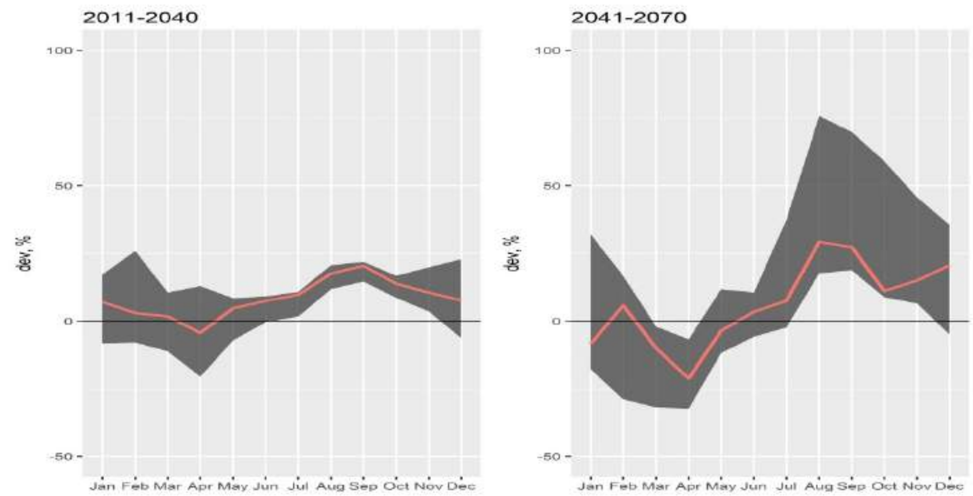

Figure 33 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Darganata gauge (after Crosa et al. (2006))

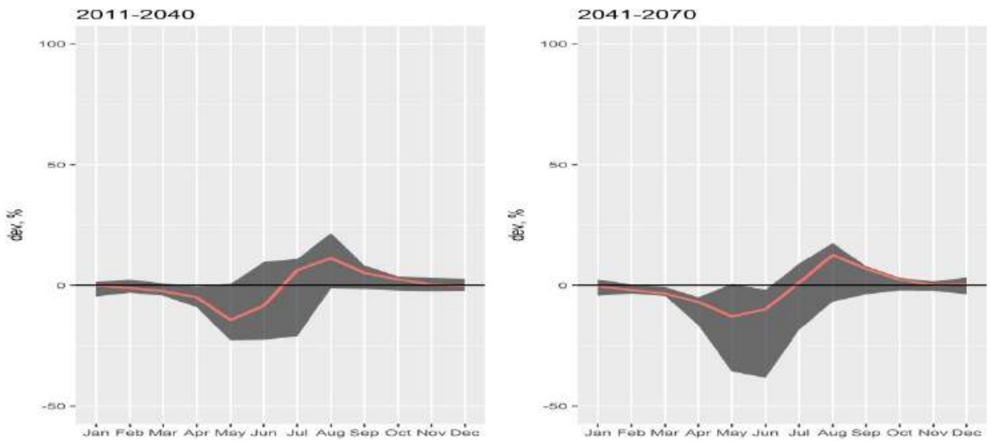

Figure 34 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Darganata gauge (own elaboration)

The trends in the mineralization levels projected for the Darganata gauge are similar to the two upstream gauges – Kerki and Chardjou: increase in the mineralization levels during summer months (up to +30%, by 2070 under high end climate change scenario) and decrease during the spring months – April and May. The projected changes in the levels of mineralization show strong correlation to the projected changes in the discharge.

Figures 36 and 37 present estimated relative changes in the levels of nitrates under two climate change scenarios. The levels of nitrates exhibit negative correlation to the discharge alteration patterns, in contrast to the upstream gauge Tartki, where the nitrates levels showed positive correlation. At the Darganata gauge the nitrates levels are projected to increase in summer when the discharge levels are projected to decrease and decrease in spring and early summer when the discharge levels are expected to increase. This allows suggestion that at the downstream part of Amu Darya the dilution processes play a big role for the nitrates levels. The nitrates levels are also shoving larger differences to the reference period, resulting in up to -25% in spring and +25% in summer and autumn under the RCP2.6 and up to +50% in autumn and summer under the RCP8.5 by the year 2070. The increase of 25% in the nitrates levels is projected already by the year 2040 under both climate change scenarios.

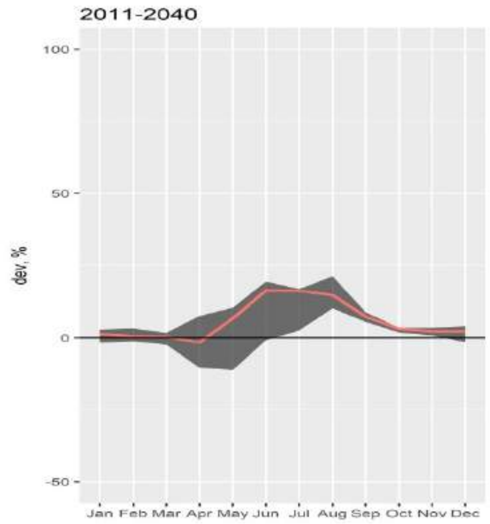

Figure 35 Relative changes in the mineralization levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Darganata gauge (own elaboration)

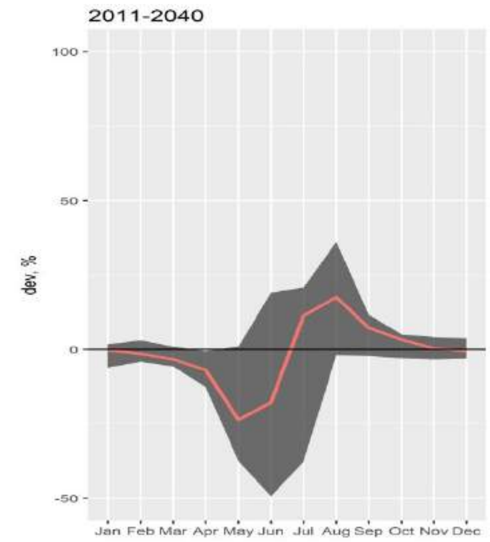

Figure 36 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP2.6 scenario for the Darganata gauge

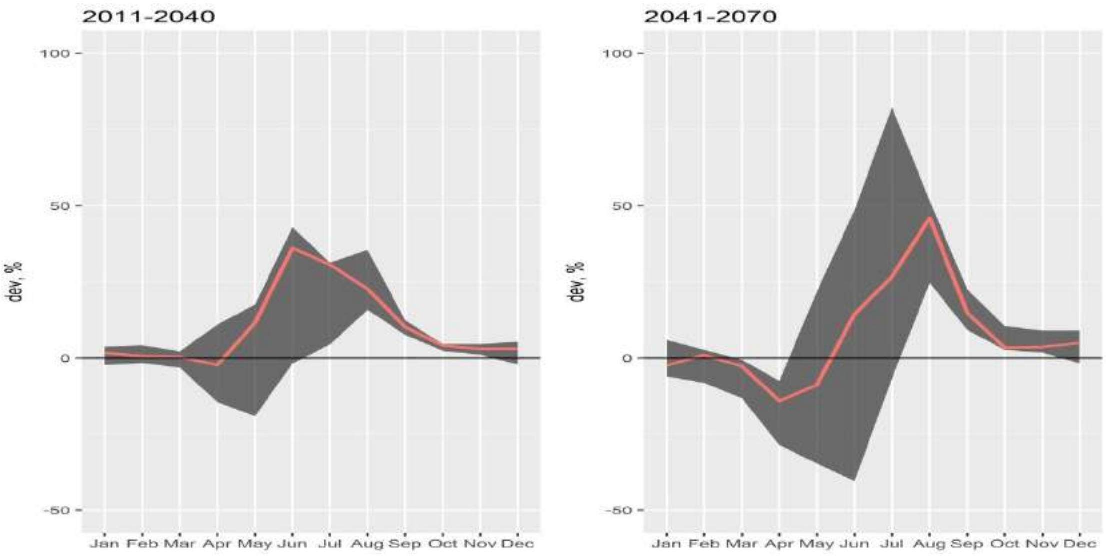

Figure 37 Relative changes in the nitrates levels for two future periods 2011-2040 and 2041-2070 relative to the baseline period of 1981-2010 under the RCP8.5 scenario for the Darganata gauge

7 Conclusions and Recommendations

Firstly, the observed data availability and quality were relatively low and further endeavours in the region should be aimed at increasing the number of sampling stations, regularity of the observations and recording of dates when the samples were made. Such information is essential even for such simple statistical analysis as correlation estimation, what can explain that not for all stations a strong correlation was found for the water quality parameters, which is associated with data scarcity and missing information of dates of sampling, as well as discharge values on that day.

The phosphorous levels are relatively high at all sampling stations and do not exhibit increasing trend in the longitudinal profile of the river, on the other hand, the phosphorous values are higher in the upstream gauges, indicating possible point source pollution, e.g. with untreated domestic waste water. The measured levels of nitrates are highest in the upstream gauges and at the Chardjou gauge.

There is a strong correlation between the mineralization and the discharge: the maximum levels of mineralization are occurring during the spring months, during the low flow period and when the leaching of the drainage water is higher. The relationship between the mineralization and discharge shows a stronger correlation for the downstream gauges, allowing the suggestion that the dilution processes have a stronger influence on the downstream water quality than the upstream. The lowest values of mineralization are observed during summer months, when the discharge levels are reaching its maximum. There was also found an inverse relationship between the phosphorous levels and discharge and direct relationship between the nitrogen and discharge for the upstream sampling stations. Such relationships are also described in the theoretical literature, therefore current conclusions can be considered as robust.

The model, proposed by Crosa et al. (2006) was also applied in order to estimate the mineralization levels at the Kerki and Darganata levels, in addition to estimated relationships, provided in this report, allowing for comparison of results.

The SWIM Model, applied in this study showed good performance in simulating the discharge at the Kelif gauging station with the monthly time step. The model was successful to represent the intra-yearly dynamics of the discharge; however the timing of the peak flows was still associated with some uncertainty, what has to be considered, when interpreting the results, described in this report. To improve the performance of the model the calibration of sub-catchments and major tributaries is recommended, as well as improvement of the model set up with the local data, e.g. more detailed data on the land use and soils, as well as observed climate data for verification of the used re-analysis dataset.

The projections of discharge of the major tributaries of the Amu Darya River – Kafirnigan, Vahsh and Pianj show no significant change in the mean annual discharge under the RCP2.6, and slight decrease under the RCP8.5. At all gauges a strong change in the intra-annual dynamics of the flow was projected - a shift of peak discharge to an earlier date (up to one month earlier under the high-end climate change scenario RCP 8.5) and moderate (RCP2.6, app. -20%) to strong (RCP8.5 up to -50%) decrease in the late summer and early autumn flows.

When looking at the selected water quality parameters, one can observe that at the upstream gauges – Tartki and Darband the impacts of altered discharge patterns show only a moderate impact on the water quality parameters under both low and high-end climate change scenario. The resulting changes show only +- 20% difference at maximum to the levels of the reference period.

When moving further downstream, changes in the mineralization levels and nitrates levels are becoming to be more significant, showing more correlation to the discharge. The shift of discharge to an earlier date and decrease of water volumes during late summer months and early autumn is projected to have negative impacts on the dissolved minerals and salts in all three gauging stations, where strong increase (up to +35% under RCP8.5 by the year 2070) in mineralization levels is projected for these periods. Also, the nitrates levels are expected to show a negative correlation to the discharge, on the contrary to the upstream gauge – showing increased levels during the periods when decrease of the discharge is projected and vice a versa. This allows the suggestion that at the downstream part of Amu Darya the dilution processes play a big role for the nitrates levels.

The projected increase of levels of mineralization by maximum 30% under the high end scenario for the downstream gauges may result in a dangerous ecological situation as the mineralization levels are already very high, reaching the limit of palatability already now. On the other hand, the higher levels of mineralization are also observed in March and April, due to leaching from the agricultural fields and shifts in the discharge may also increase the dilution of salts in these months, increasing the water quality.

The phosphorous levels were not considered in this report as no strong statistical correlation was found to the discharge. This can be explained by low number of observations, as well as the absence of the date of observation. However, from the graphs it can be seen that there is a negative correlation between the phosphorous levels and the discharge, allowing assumption that altered seasonal patterns of the discharge will also affect the seasonal dilution of the increased phosphorous levels.

Under the RCP 2.6 climate change scenario, only slight changes in the water quality parameters are observed for the upstream part and moderate changes in the downstream part. This allows an assumption that climate change may have a slight impact on the hydrological patterns of the system and therefore the important dilution processes under low-end climate change scenario. On the other hand, the Amu Darya River is a system strongly affected by anthropogenic activities, which in the future may also outweigh the impact of climate change. However, there is no doubt that for the downstream reaches, the impacts of climate change will likely exacerbate the water quality problems.

The results of the current analysis allow us to make an assumption that the downstream parts of the Amu Darya catchment, belonging to Uzbekistan and Turkmenistan will suffer more from the impacts of climate change on the water quality, rather than those in the upstream. Of course, this assumption will be held only if the loads of pollutants and their discharges will remain on the same levels as observed in the past. At the later stage, to deepen the analysis of the changes, triggered by projected climate change in the discharge patterns it will be important to analyse how the frequency and values of low (Q90, Q95) and high flows (Q5, Q10) will be changing in the future, as they will also have a direct impact on the mineralization levels.

This analysis also shows that depending on the estimated statistical relationships between the discharge and water quality parameters the results of impacts may be very different. E.g. the projections obtained by authors elaboration based on the data, received from the project partners and by Crosa et al (2006) are quite different in their scales, Corsa et al. (2006) showing more moderate impacts. This illustrates how different the estimations may be, depending on the statistical model used, suggesting that a physically or process-based model may be a more suitable tool for such analysis. In order to perform a thorough analysis of the water quality parameters, a proper water quality model, supported by good quality observational data has to be set up. On the other hand, as discussed above such tools also require much more input data for set up and through information about pollutants loads from the point and diffusion sources in the entire catchment, which also may be absent.

Such analysis as performed in this report should be taken with caution and can be considered only as supportive information, being treated by no means as a forecast, but rather as a first approximation of projected impacts of climate change on the water quality parameters.

8 References

Crosa, G, J Froebrich, V Nikolayenko, F Stefani, P Galli, D Calamari, and Amu Darya. 2006. “Spatial and Seasonal Variations in the Water Quality of the Amu Darya River (Central Asia).” *Water Research* 40: 2237–45. doi:10.1016/j.watres.2006.04.004.

Hempel, S., K. Frieler, L. Warszawski, J. Schewe, and F. Piontek. 2013. “A Trend-Preserving Bias Correction – the ISI-MIP Approach.” *Earth System Dynamics* 4 (2): 219–36. doi:10.5194/esd-4-219-2013.

Krysanova, V, DI Müller-Wohlfeil, and A Becker. 1998. “Development and Test of a Spatially Distributed Hydrological/Water Quality Model for Mesoscale Watersheds.” *Ecological Modelling*, no. 106: 261–89. http://www.sciencedirect.com/science/article/pii/S0304380097002044.

Lobanova, A., I. Didovets, C. Menz, V. Krysanova, and F. Hattermann. 2017. “Summary on Climate Change Projections and Hydrological Impacts for Small Pilot Areas in the Aral Sea Basin (the Aspara and Isfara Catchments and the Priaralye District).” Potsdam, Germany.

Panagos, Panos, Marc Van Liedekerke, Arwyn Jones, and Luca Montanarella. 2012. “European Soil Data Centre: Response to European Policy Support and Public Data Requirements.” *Land Use Policy* 29 (2): 329–38. doi:10.1016/j.landusepol.2011.07.003.

SIC ICWC. 2011. “WATER QUALITY IN THE AMUDARYA AND SYRDARYA RIVER BASINS Analytical Report.” Tashkent.

Weedon, GP, S Gomes, P Viterbo, H Oestrle, JC Adam, N Bellooin, O Boucher, and M Best. 2010. “Technical Report No . 22. The WATCH Forcing Data 1958-2001: A Meteorological Forcing Dataset for Land Surface and Hydrological Models.”

ANNEX 1

Total number of observations per month at five stations

Month	Discharge	Mineralization	Suspended matter	pH	NO2	NO3	Total N	P
Tartki								
Jan	14	9	6	9	8	7	9	5
Feb	14	6	3	6	5	5	6	4
Mar	14	4	2	4	3	3	3	1
Apr	14	7	4	7	7	6	7	4
May	14	8	6	8	8	7	8	5
Jun	14	8	6	8	7	7	8	5
Jul	14	9	7	9	7	6	7	8
Aug	14	4	1	4	4	4	4	3
Sep	14	4	3	5	4	4	5	3
Oct	14	4	3	5	4	3	4	2
Nov	13	6	4	7	7	4	7	3
Dec	14	8	6	9	9	7	9	5
Darband								
Jan	21	12	11	14	15	12	15	7
Feb	21	6	5	8	8	6	8	3
Mar	21	13	8	14	14	12	14	8
Apr	21	12	9	12	13	11	14	6
May	21	19	15	21	21	20	20	14
Jun	21	11	9	13	11	11	11	8
Jul	21	10	7	11	10	9	10	6
Aug	21	13	9	14	13	14	15	10
Sep	21	5	3	6	7	7	7	5
Oct	21	5	5	9	6	6	9	3
Nov	21	11	9	17	16	14	15	9
Dec	21	10	6	13	13	9	13	6
Kerki								
Jan	26	14	2	14	14	14	17	14
Feb	26	12	2	12	12	12	17	12
Mar	26	13	1	13	13	13	16	13

Apr	26	14	2	14	14	14	16	14
May	26	10	3	10	10	10	16	10
Jun	26	14	2	14	14	14	16	14
Jul	26	13	2	13	13	13	16	13
Aug	26	14	3	15	14	14	16	15
Sep	26	8	2	8	8	8	16	8
Oct	26	2	1	2	2	2	16	2
Nov	26	11	2	11	10	11	16	10
Dec	26	12	1	12	12	12	16	12
Chordjou								
Jan	25	18	4	18	18	18	16	18
Feb	25	16	4	16	16	15	16	16
Mar	26	16	3	16	16	16	16	16
Apr	26	16	2	16	16	16	16	16
May	26	16	3	16	16	16	16	16
Jun	26	16	2	16	15	16	16	15
Jul	26	15	1	15	15	15	16	15
Aug	26	18	1	18	18	18	16	18
Sep	26	10	2	10	10	10	16	10
Oct	26	4	1	4	4	4	16	4
Nov	26	9		9	9	9	16	9
Dec	26	13	1	13	13	13	16	13
Darganata								
Jan	26	15	19	14	15	15	16	14
Feb	26	9	1	8	9	9	16	8
Mar	26	12	1	11	12	12	16	11
Apr	26	12	1	11	12	12	16	11
May	26	13	2	11	13	13	17	11
Jun	26	12	1	11	12	12	16	11
Jul	26	11	1	10	11	11	16	10
Aug	26	12	1	11	12	12	16	11
Sep	26	8	1	7	8	8	16	7
Oct	26	3	1	2	3	3	16	2
Nov	26	9	1	8	9	9	16	8
Dec	26	12	1	11	12	12	16	11

Schematic Representation of drainage channel network of the Amu Darya River (source BWO "Amudarya")

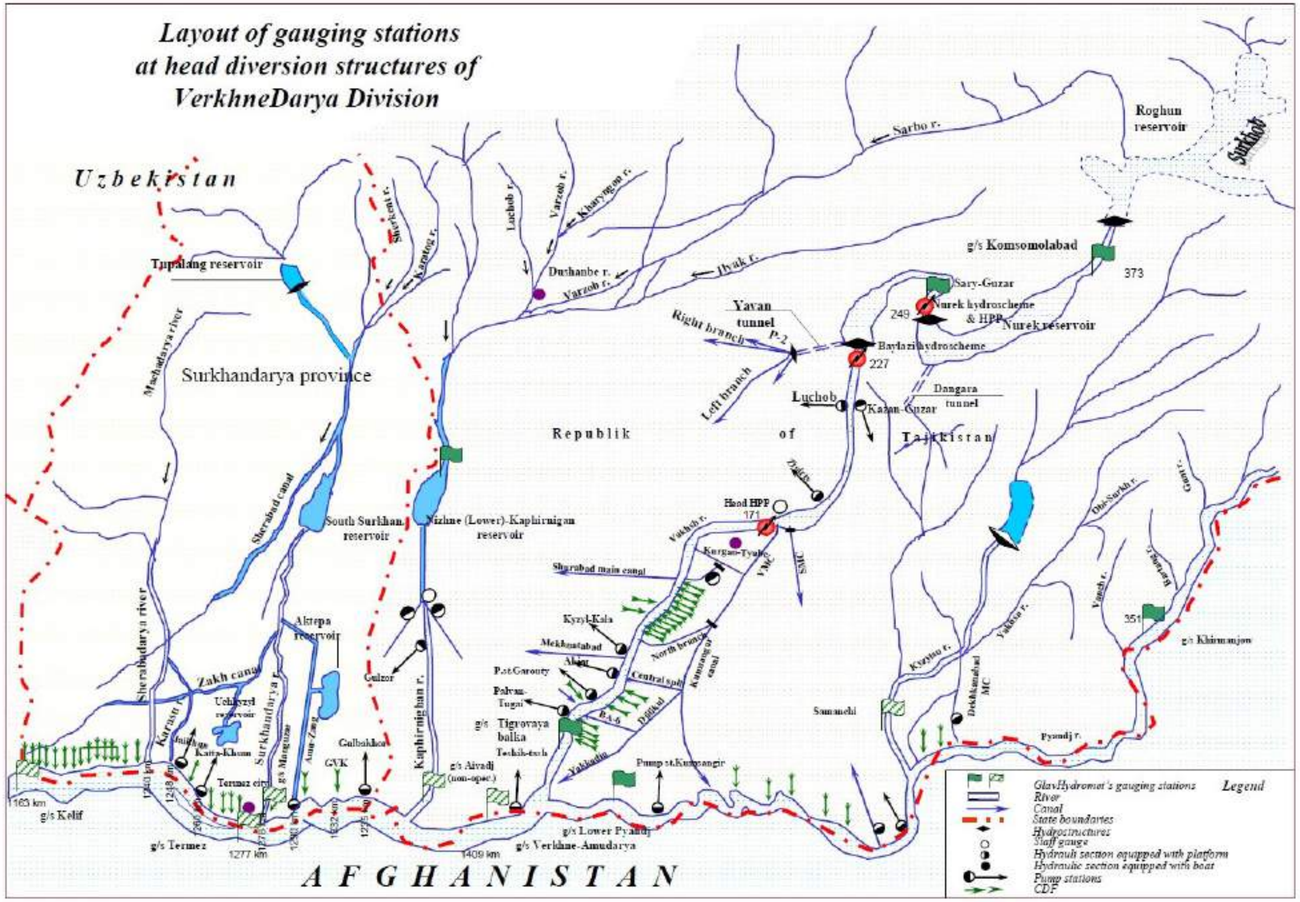

Figure A1 Schematic representation of gauging stations, drainage channel networks and hydraulic structures in the upstream part of the Amu Darya River Basin

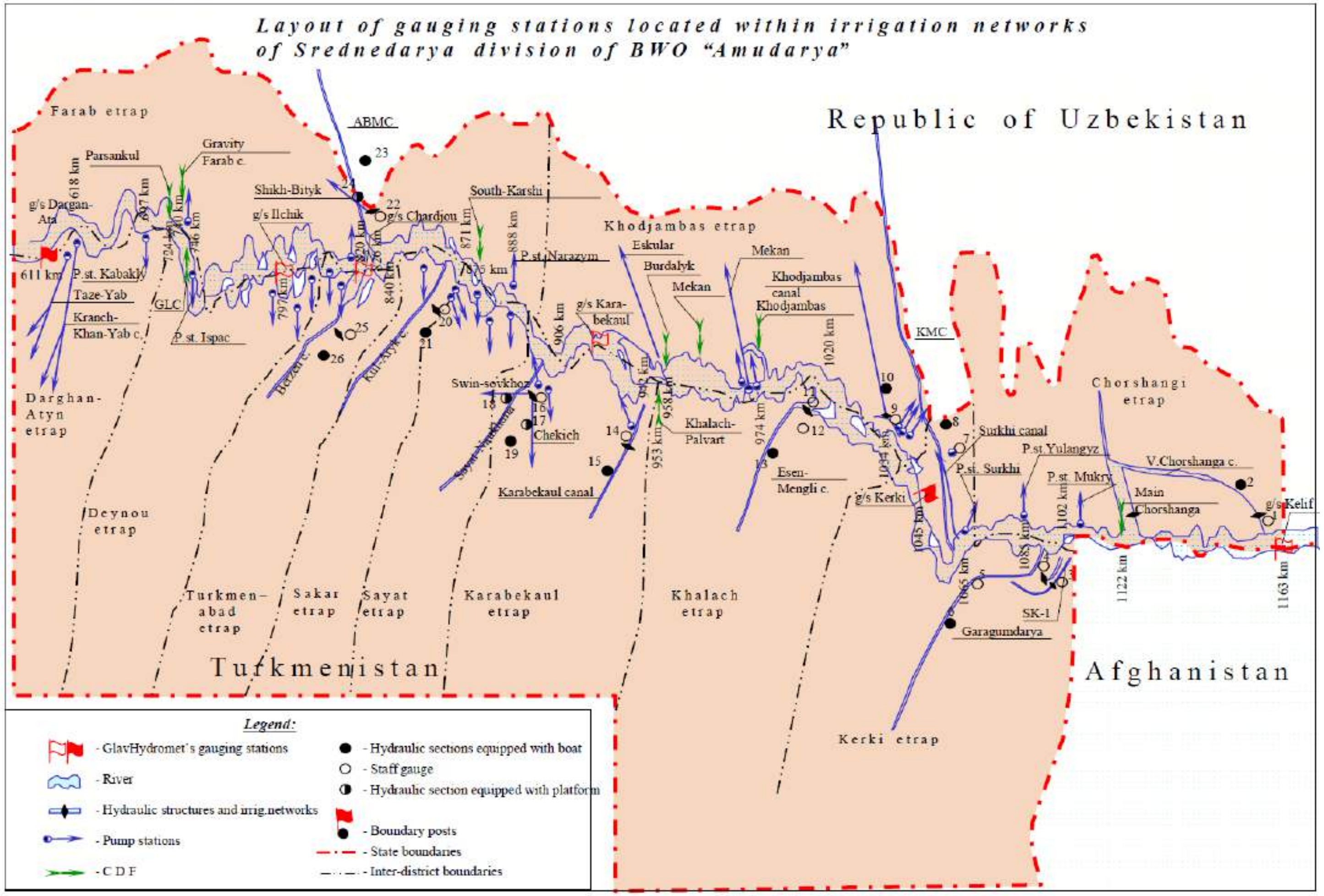

Figure A2 Schematic representation of gauging stations, drainage channel networks and hydraulic structures in the middle part of the Amu Darya River Basin

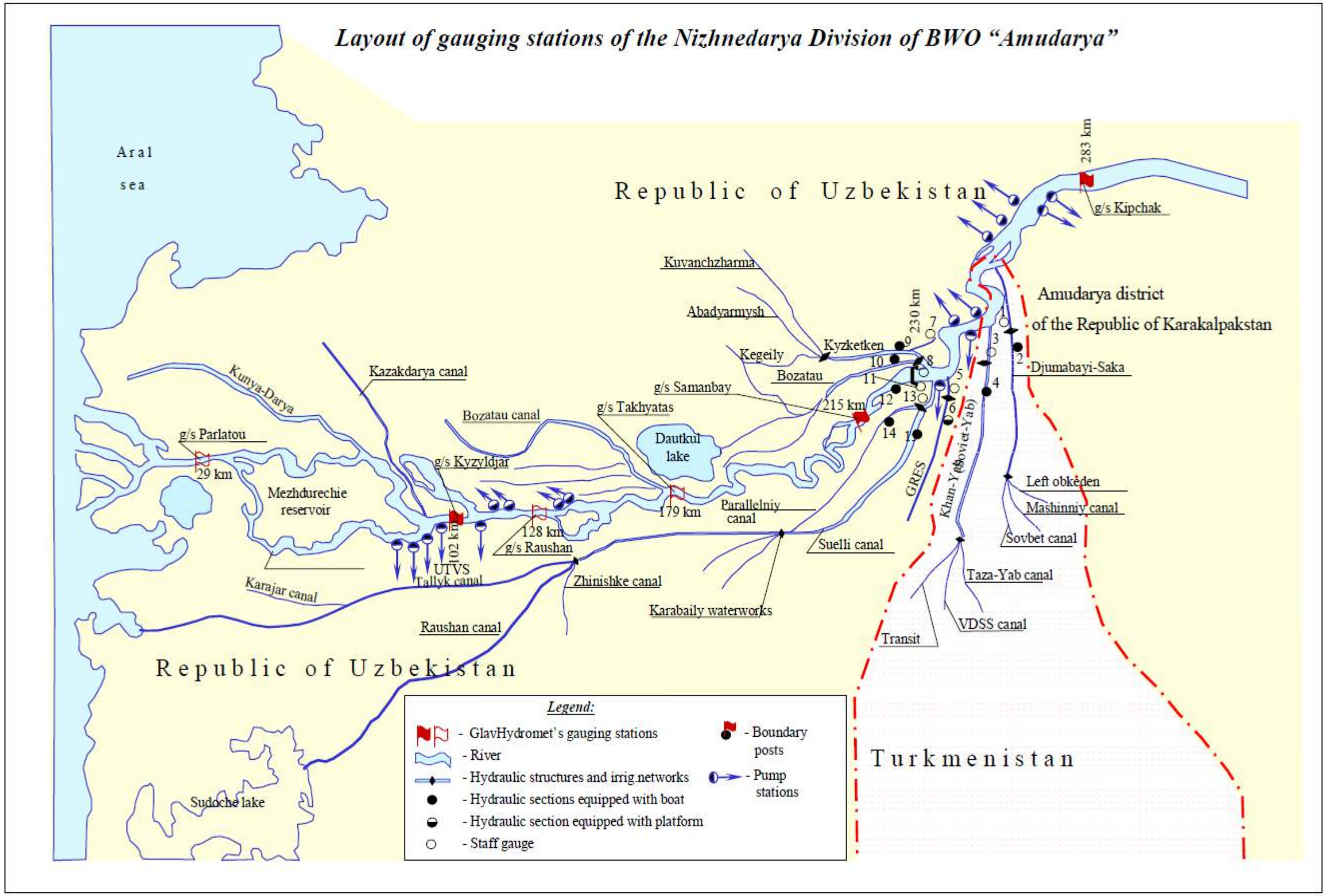

Figure A3 Schematic representation of gauging stations, drainage channel networks and hydraulic structures in the lower part of the Amu Darya River Basin

ANNEX II

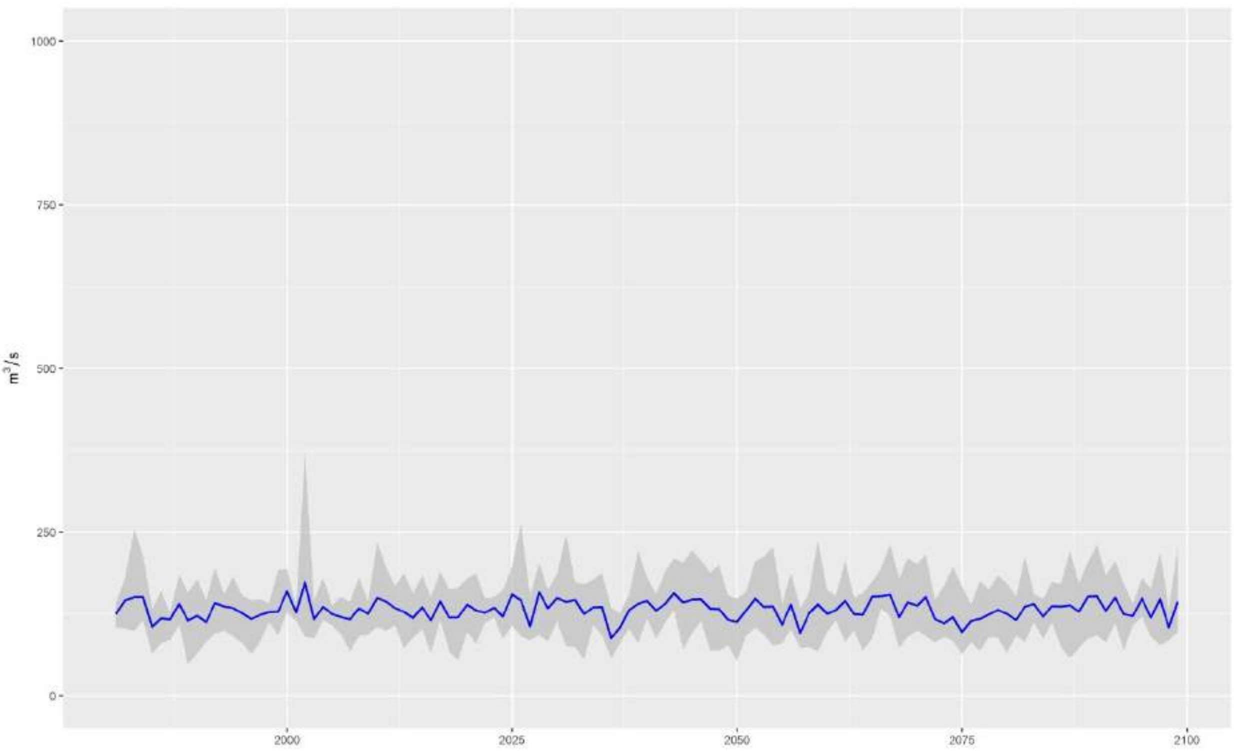

Fig A4 Mean annual discharge projections at the Tartki gauging station under RCP2.6

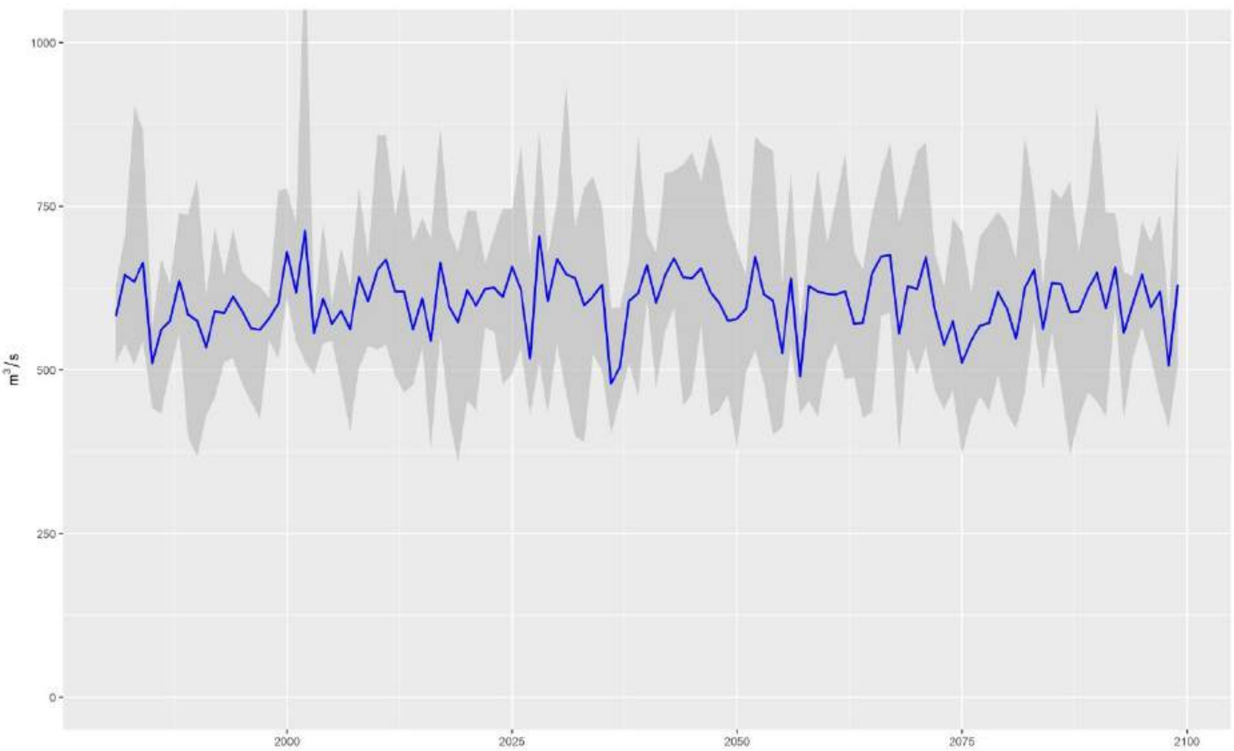

Fig A5 Mean annual discharge projections at the Kizyl Kala gauging station under RCP2.6

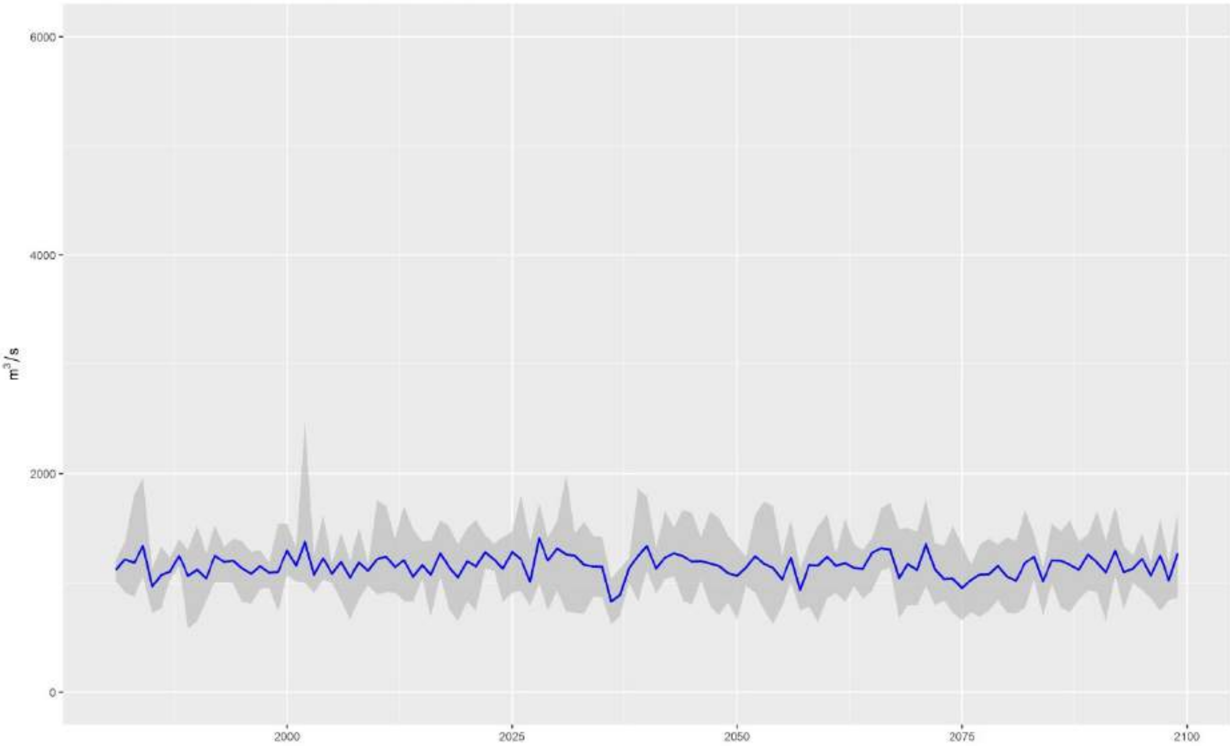

Fig A6 Mean annual discharge projections at the Nizhniy Pianj gauging station under RCP2.6

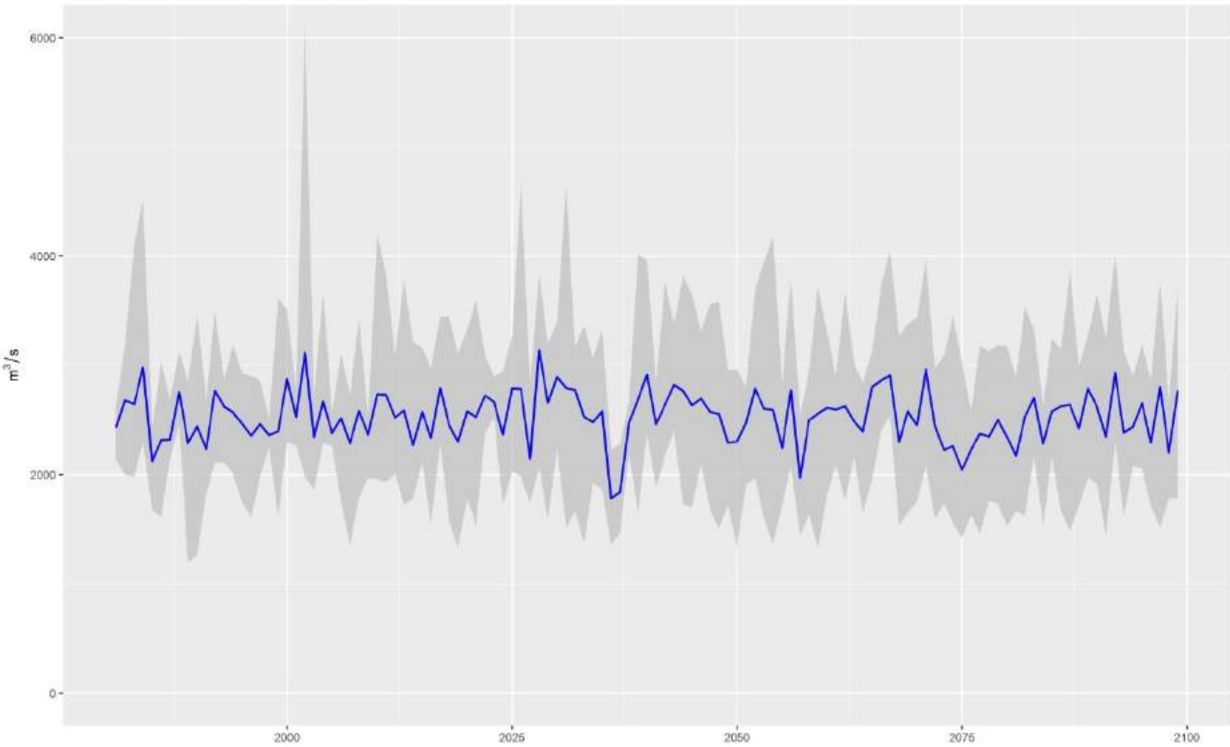

Fig A7 Mean annual discharge projections at the Kelif gauging station under RCP2.6

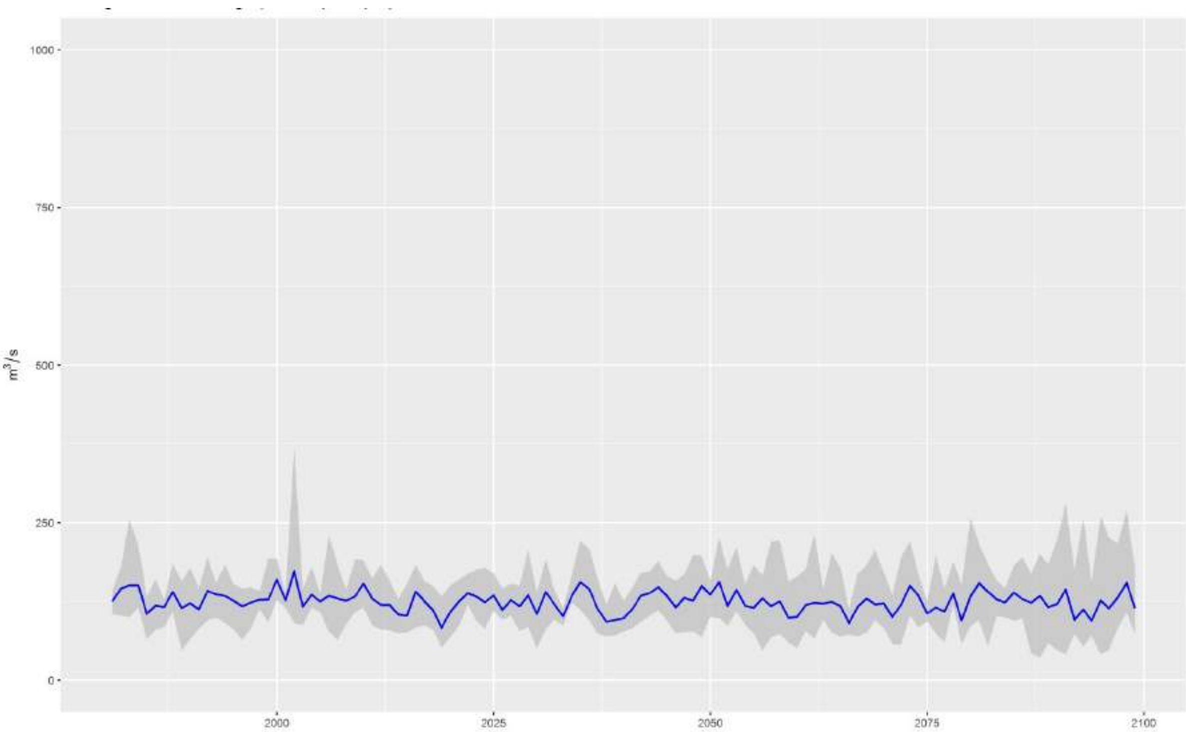

Fig A8 Mean annual discharge projections at the Tartki gauging station under RCP8.5

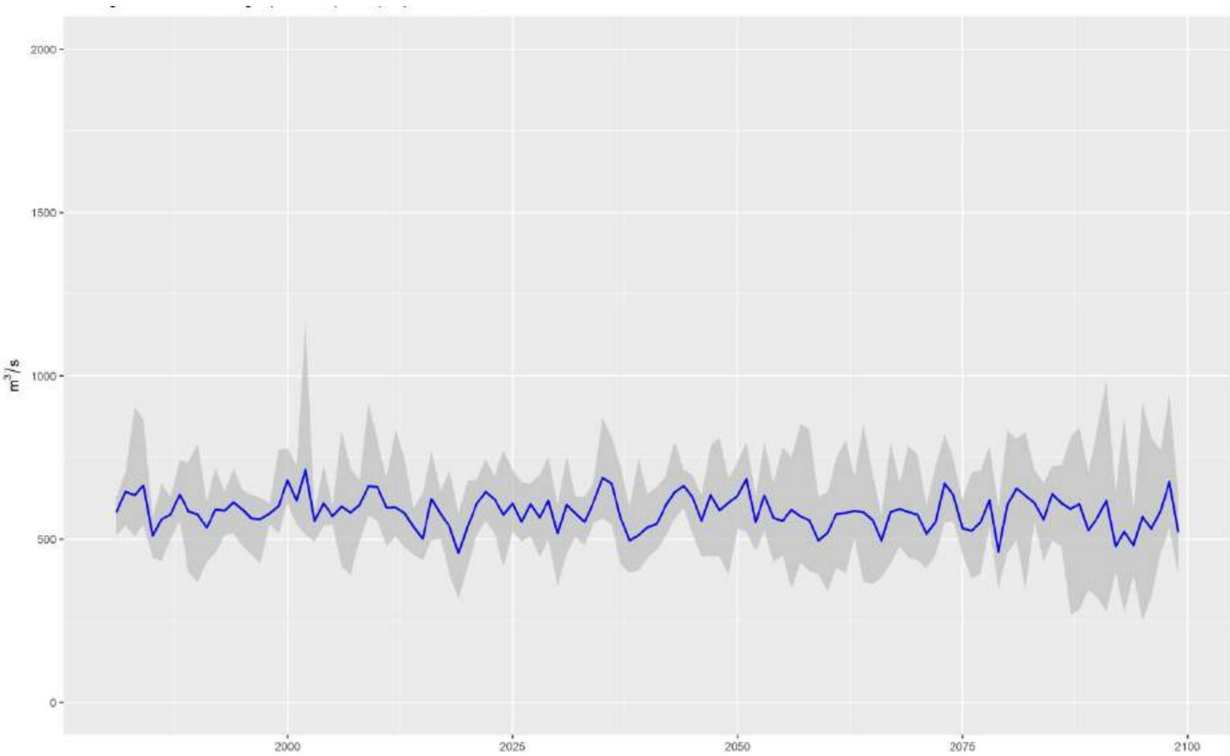

Fig A9 Mean annual discharge projections at the Kizyl Kala gauging station under RCP8.5

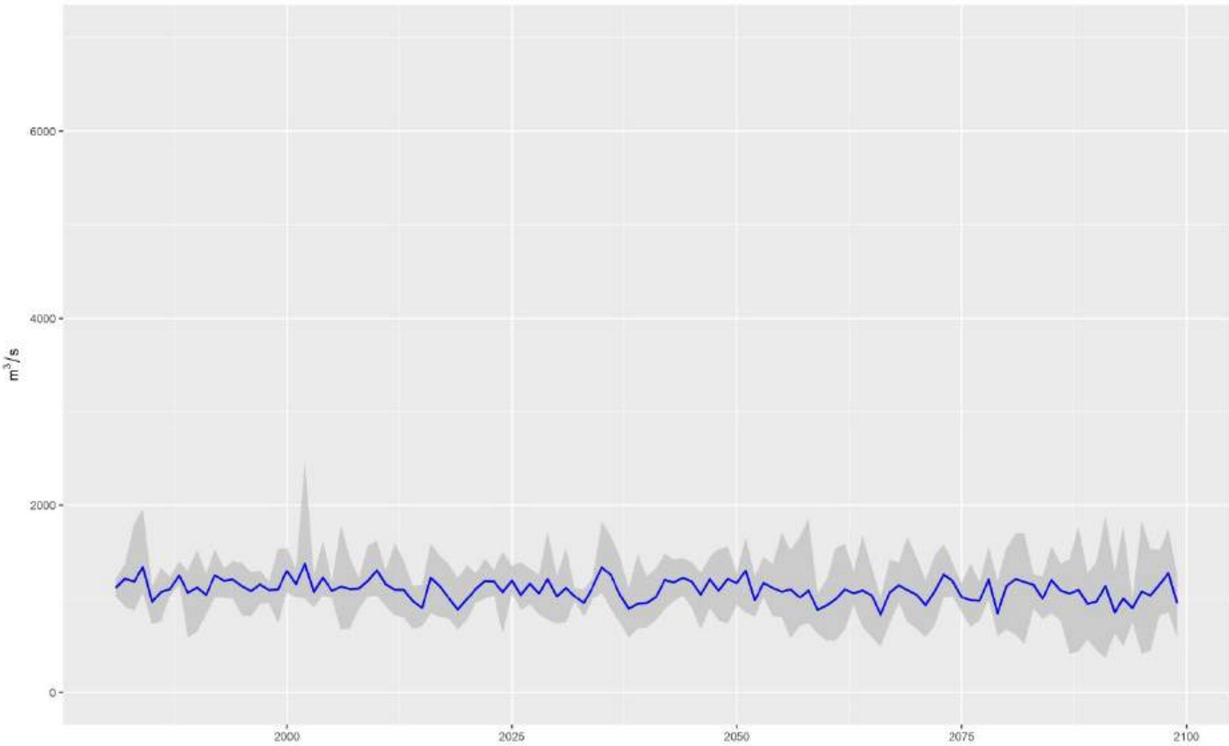

Fig A10 Mean annual discharge projections at the Nizhniy Pianj gauging station under RCP8.5

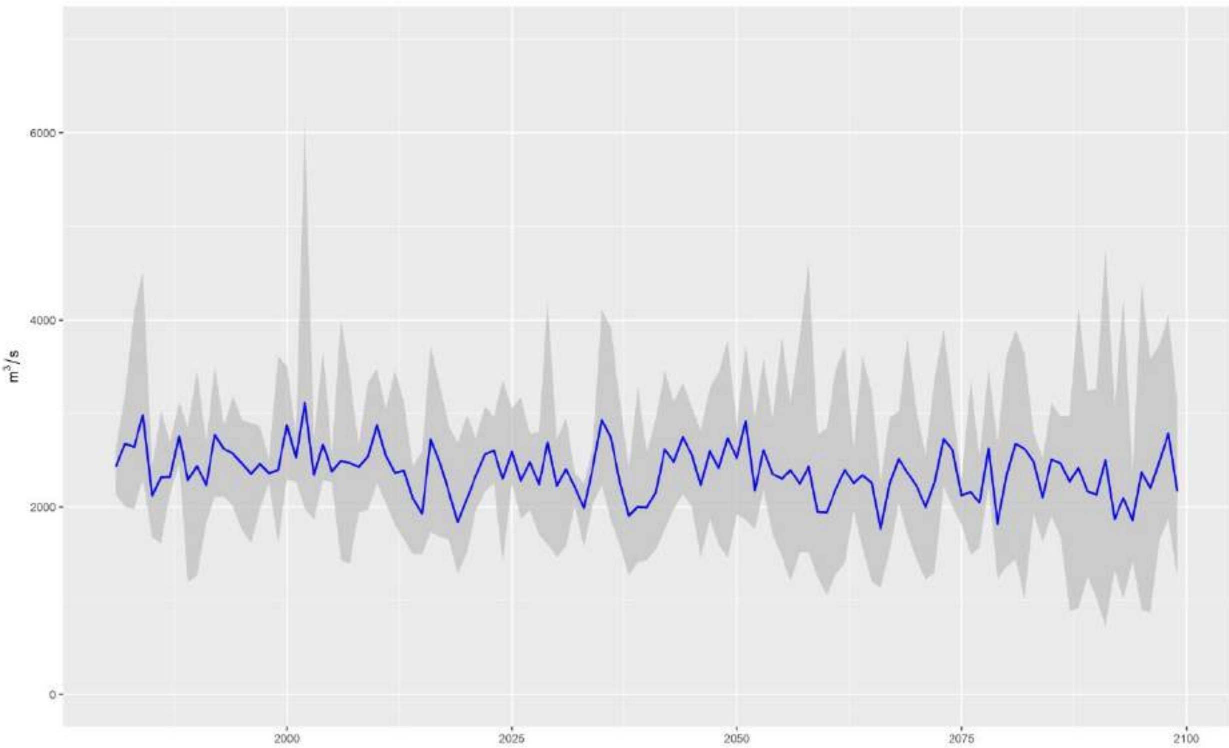

Fig A11 Mean annual discharge projections at the Kelif gauging station under RCP8.5

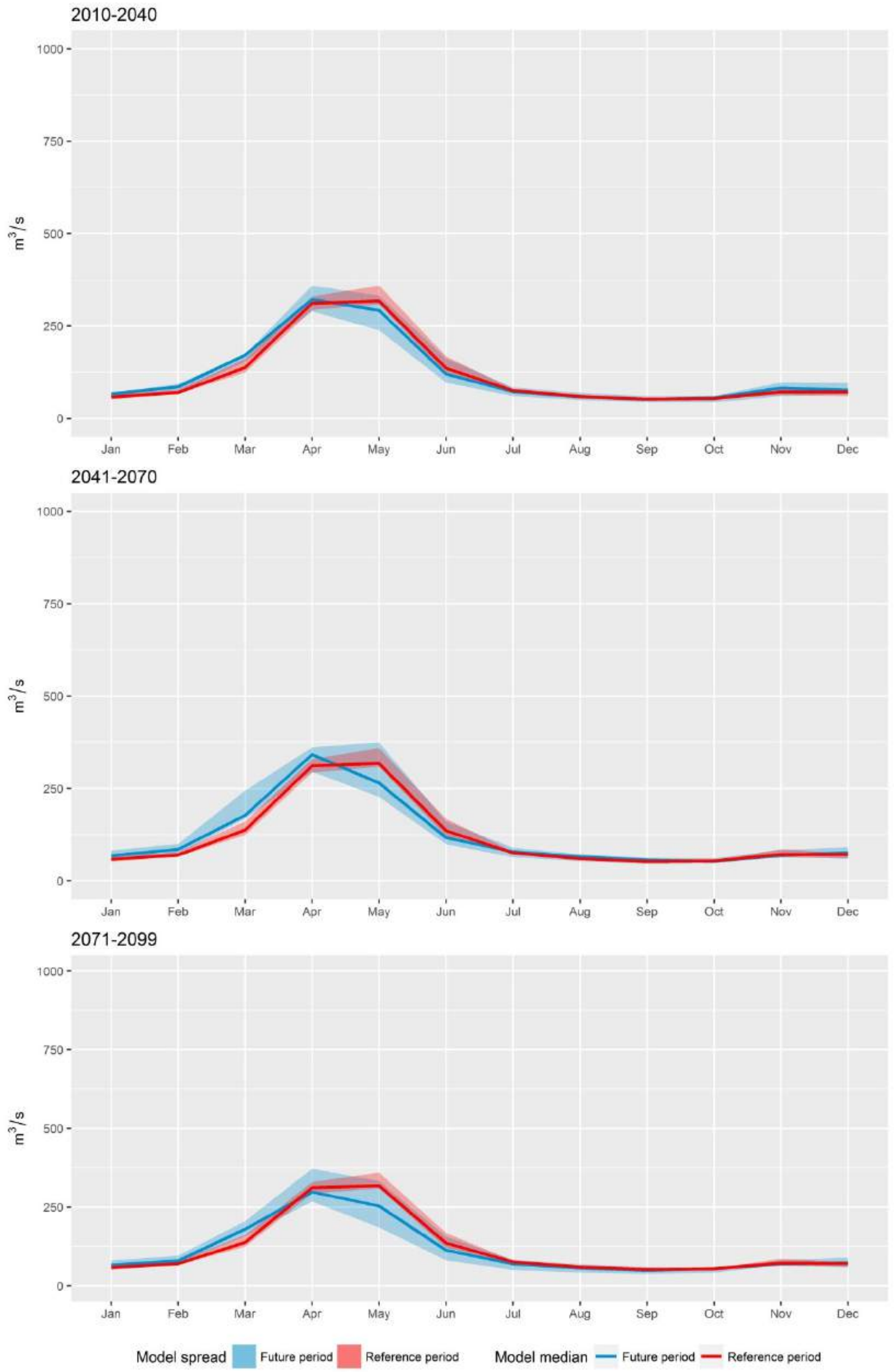

Fig A12 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Tartki gauging station under the RCP2.6 scenario for reference and three future periods

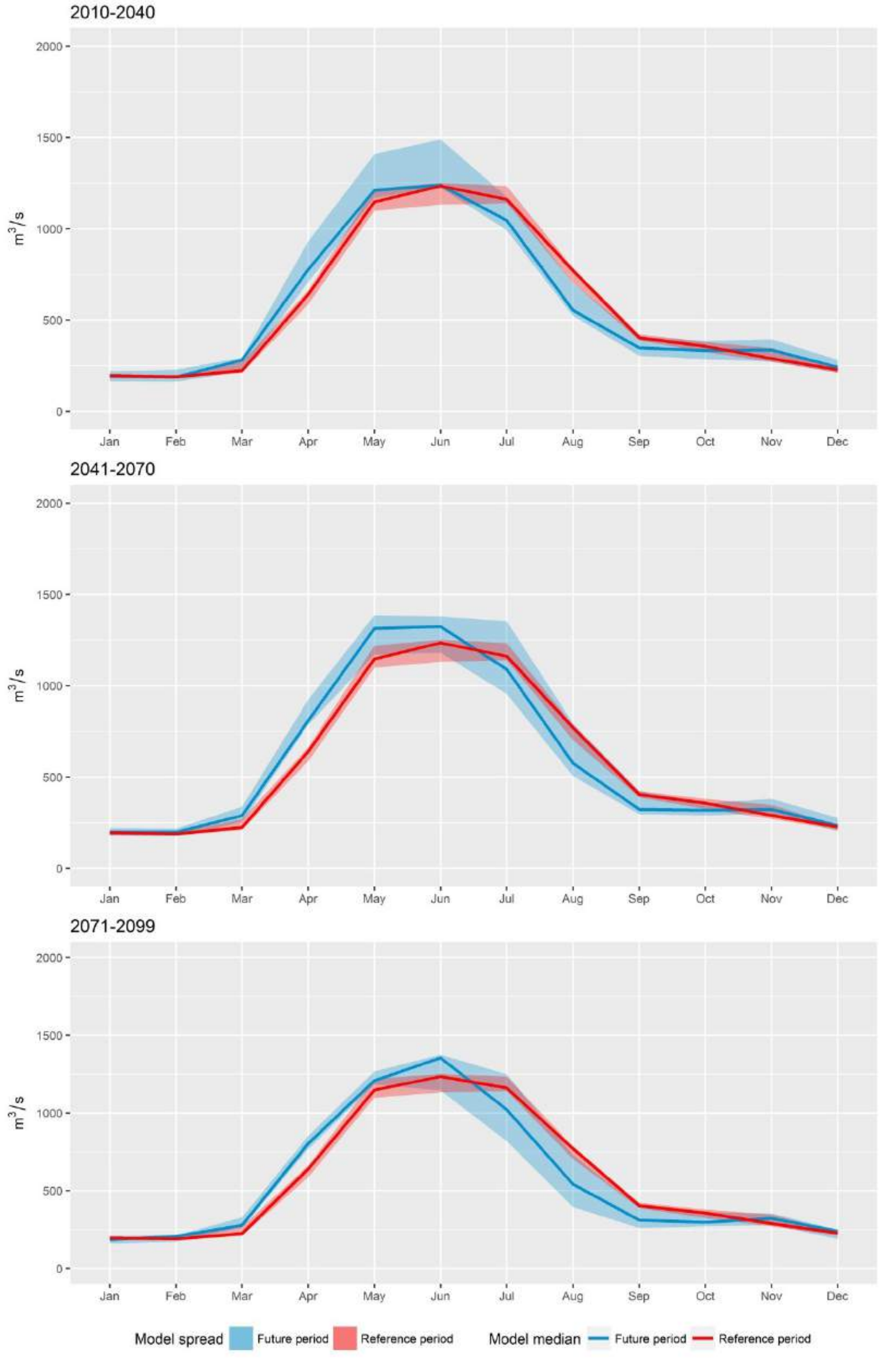

Fig A13 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Kizyl Kala gauging station under the RCP2.6 scenario for reference and three future periods

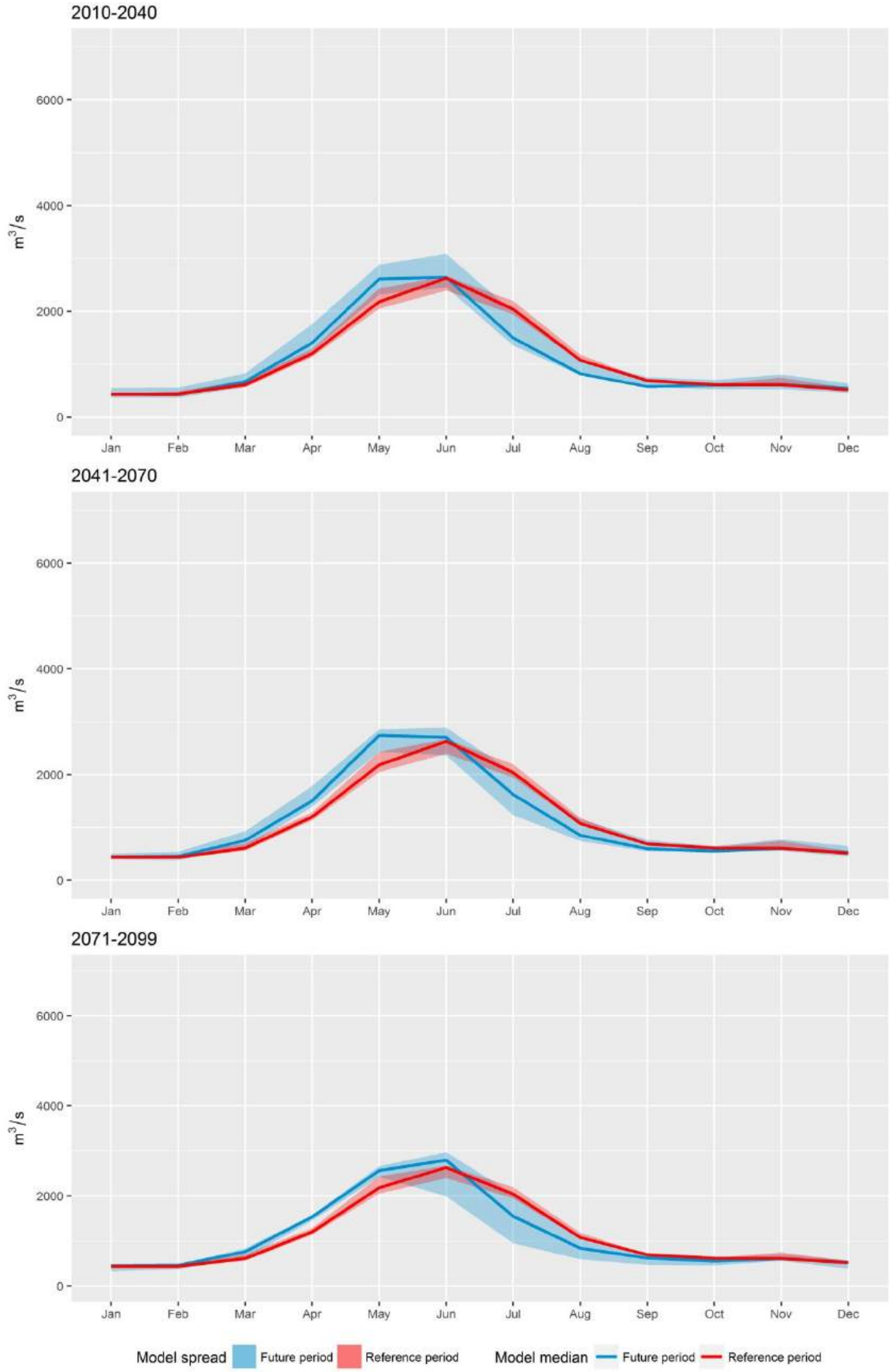

Fig A14 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Nizhniy Pianj gauging station under the RCP2.6 scenario for reference and three future periods

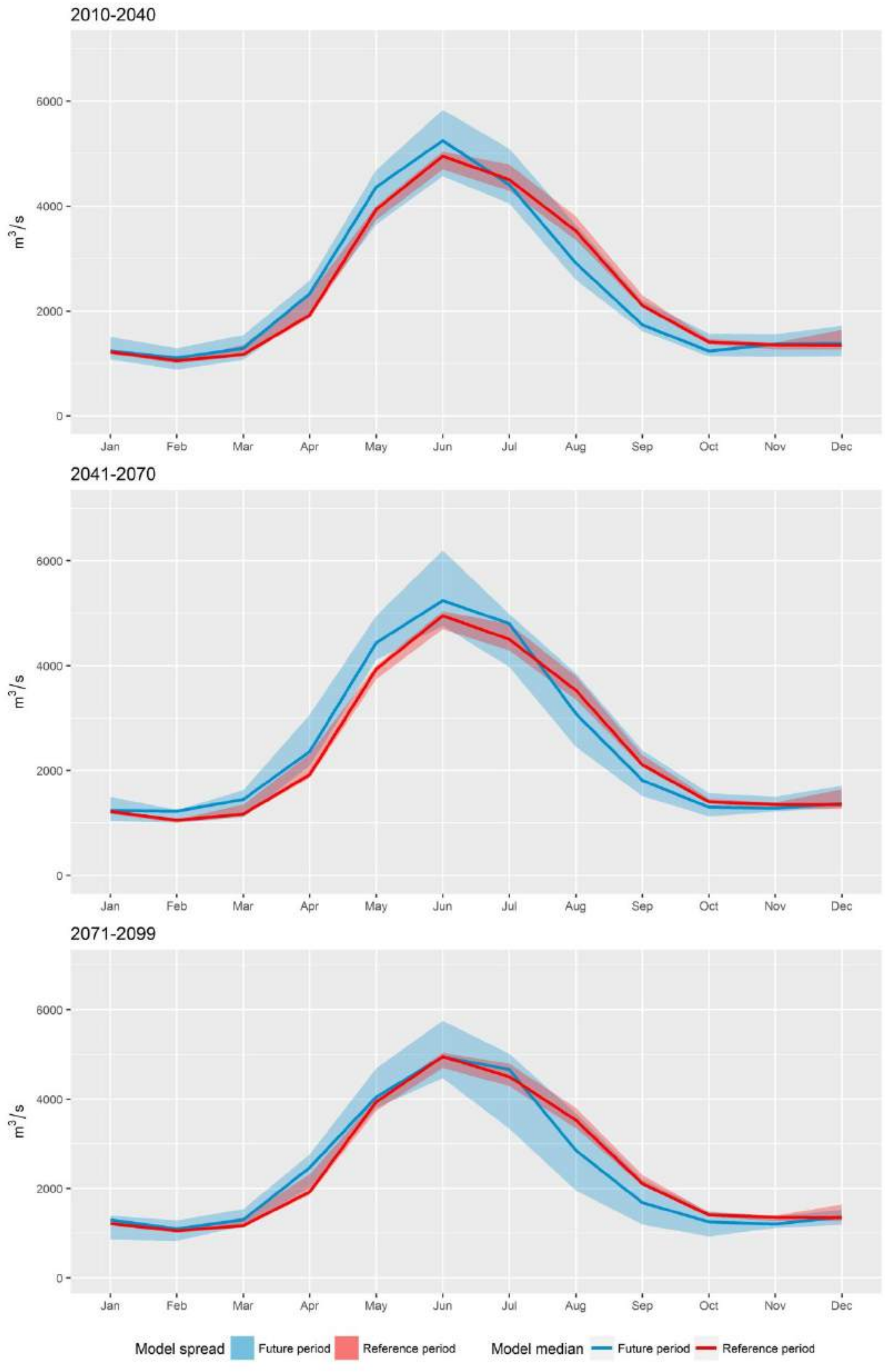

Fig A15 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Kelif gauging station under the RCP2.6 scenario for reference and three future periods

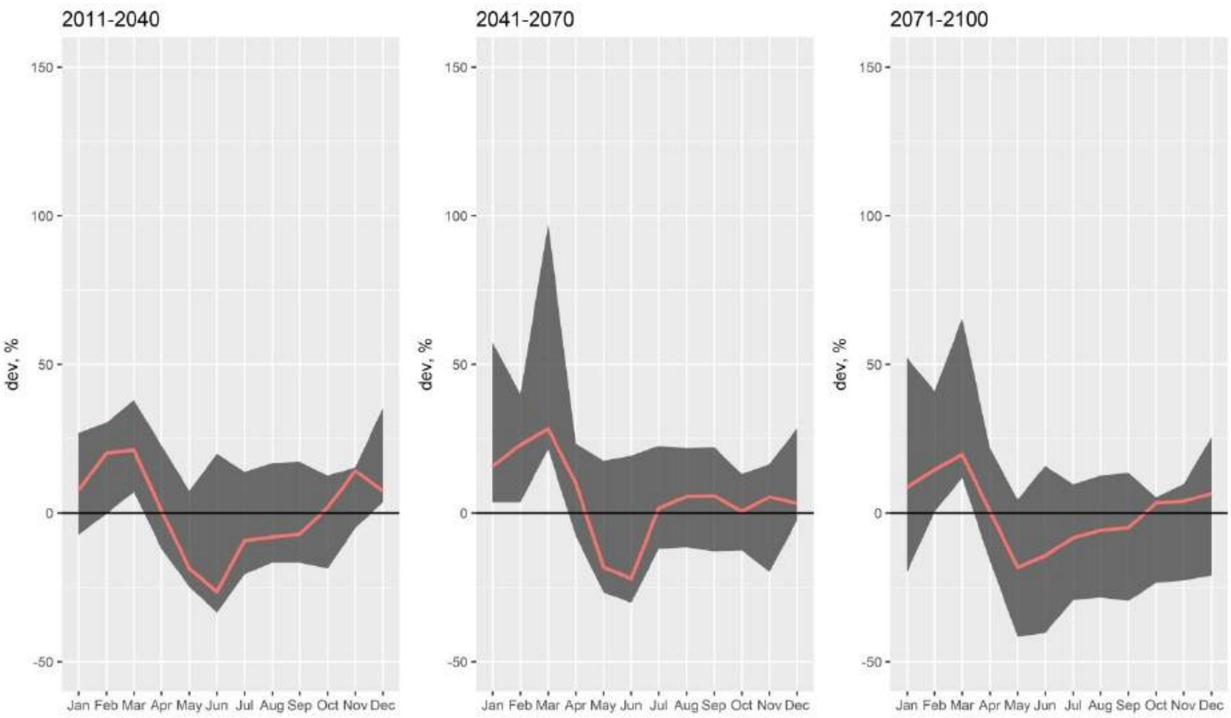

Fig A16 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Tartki gauging station under the RCP2.6 scenario

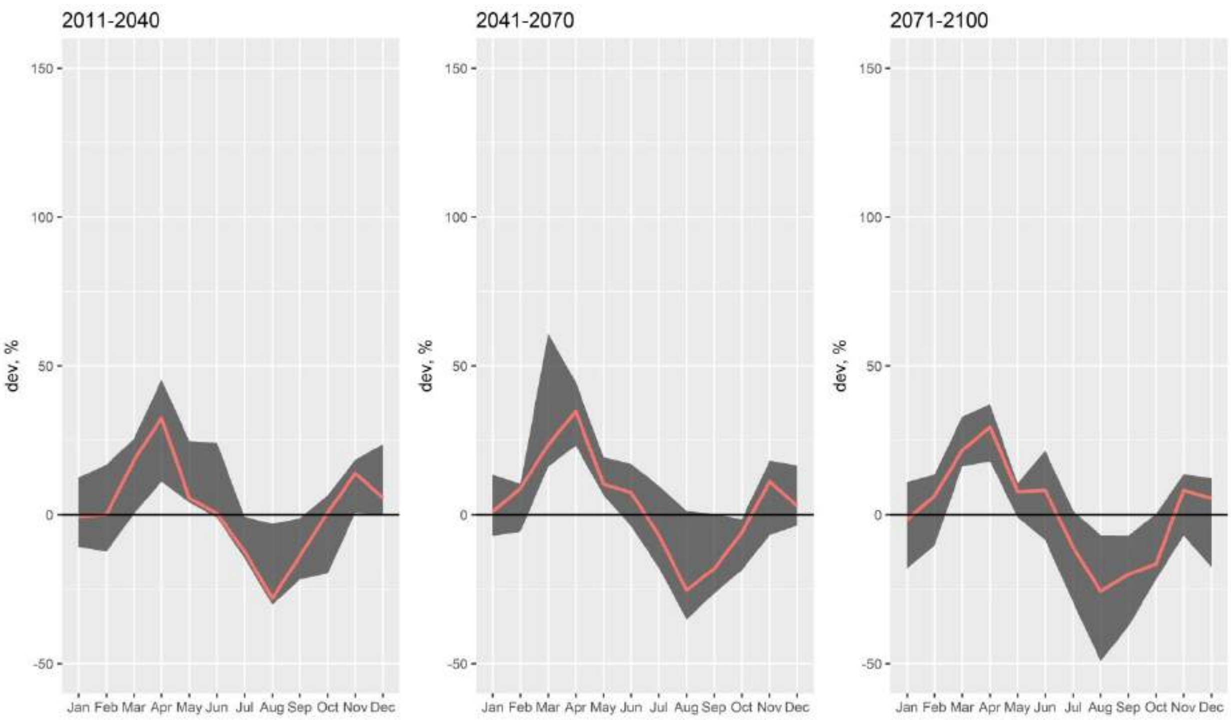

Fig A17 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Kizyl Kala gauging station under the RCP2.6 scenario

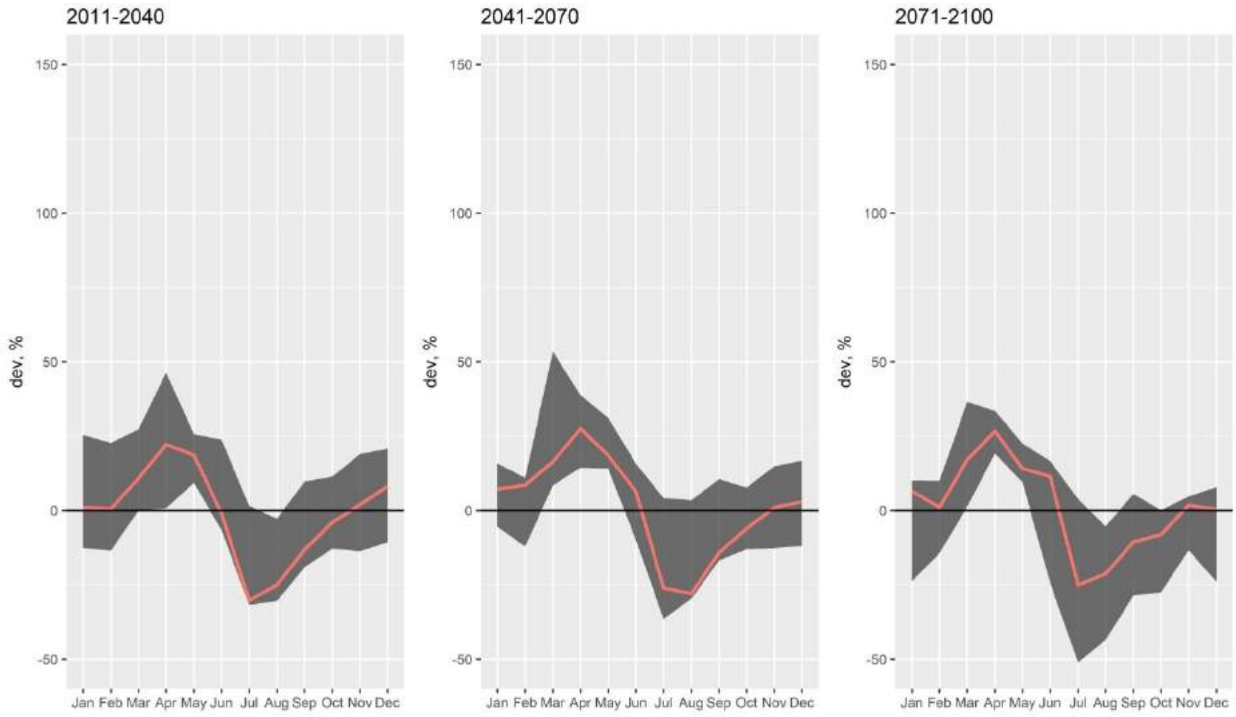

Fig A18 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Nizhniy Pianj gauging station under the RCP2.6 scenario

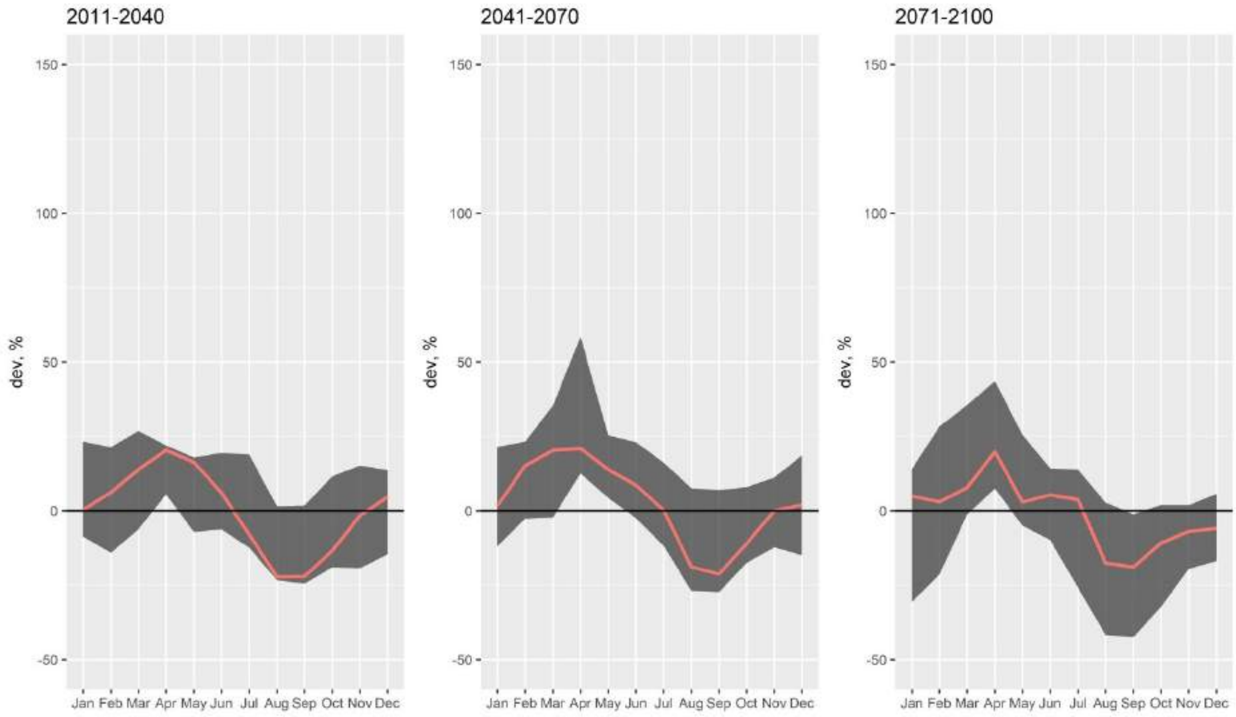

Fig A19 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Kelif gauging station under the RCP2.6 scenario

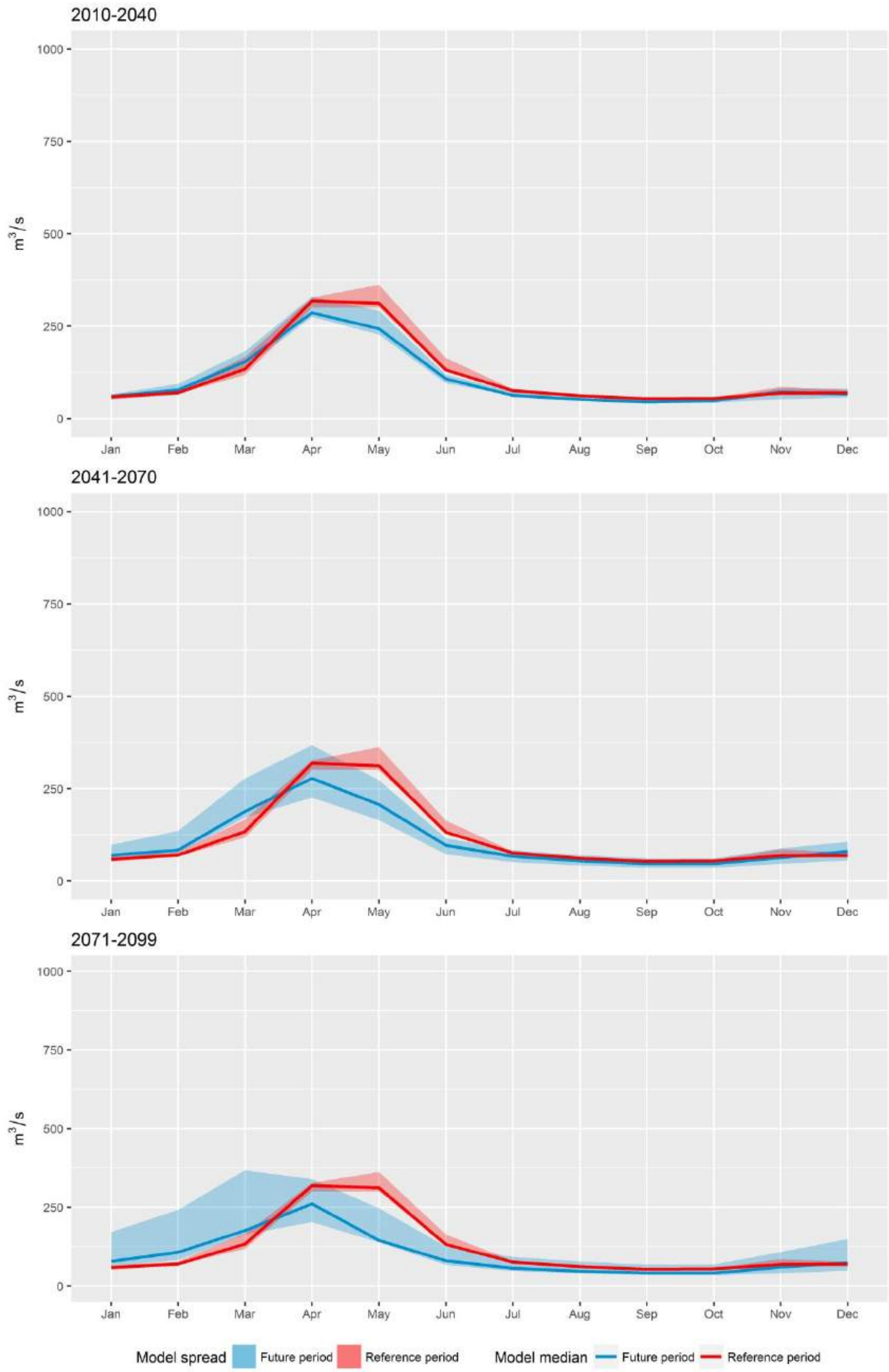

Fig A20 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Tartki gauging station under the RCP8.5 scenario for reference and three future periods

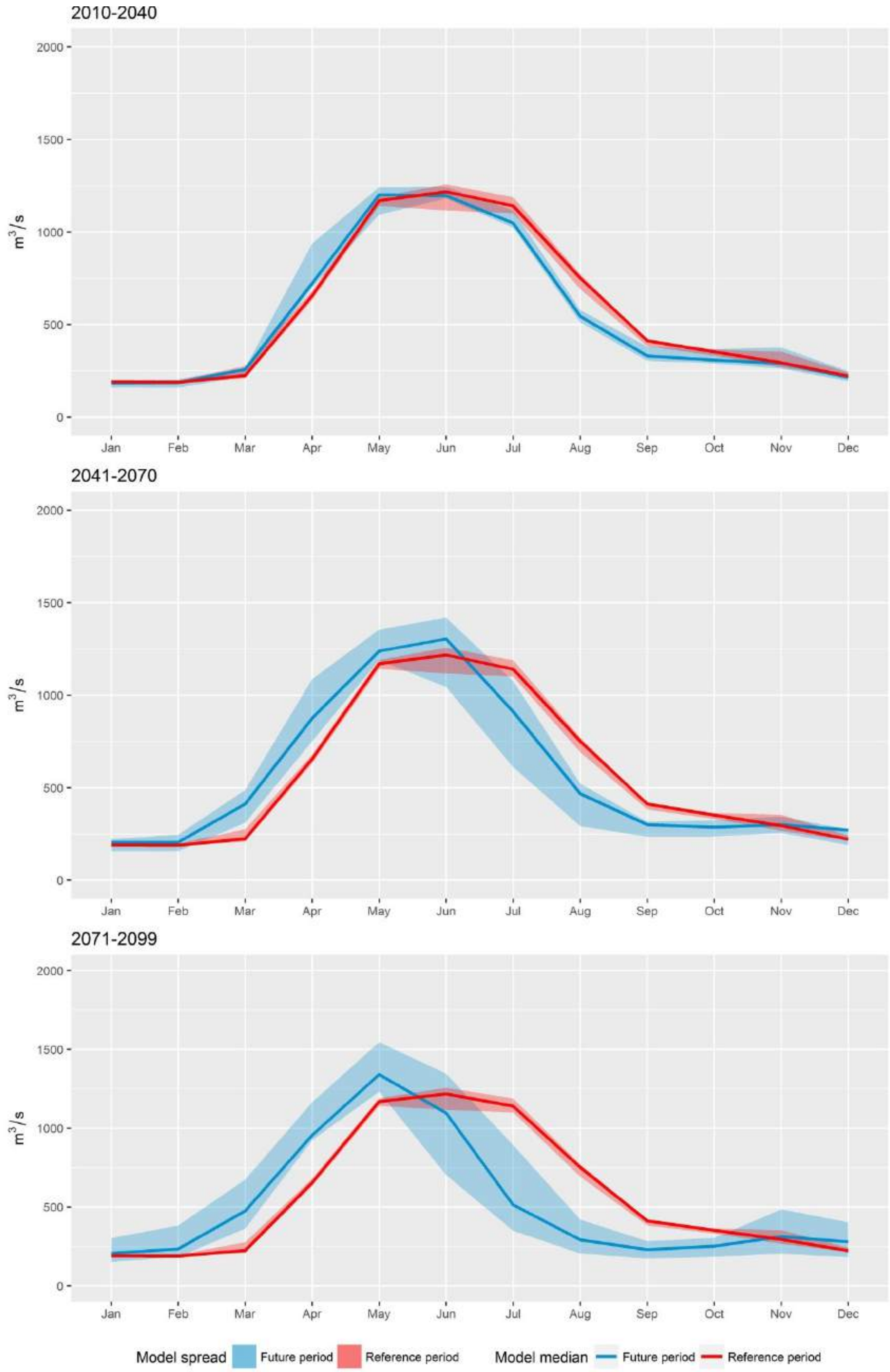

Fig A21 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Kizyl Kala gauging station under the RCP8.5 scenario for reference and three future periods

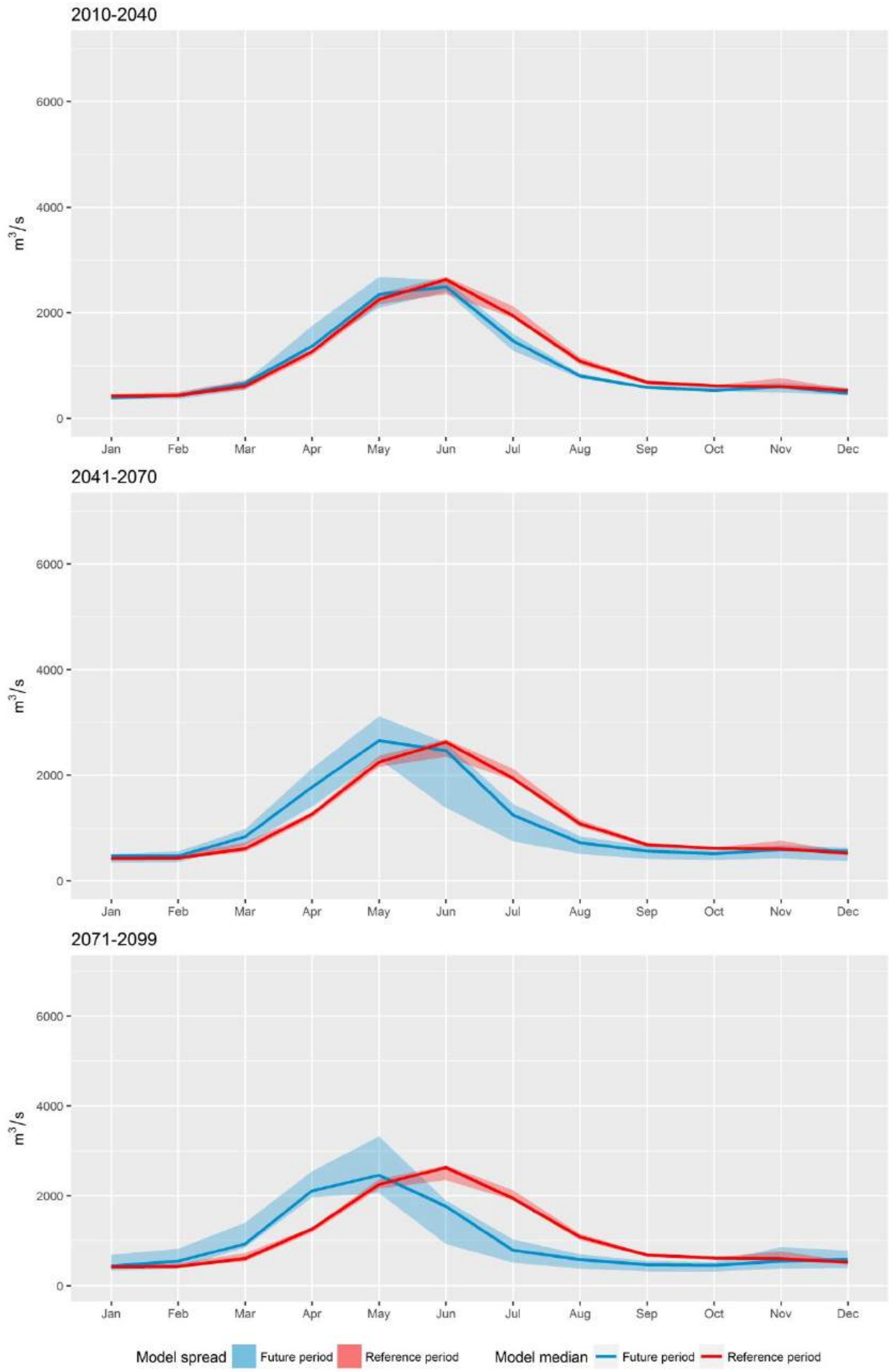

Fig A22 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Nizhniy Pianj gauging station under the RCP8.5 scenario for reference and three future periods

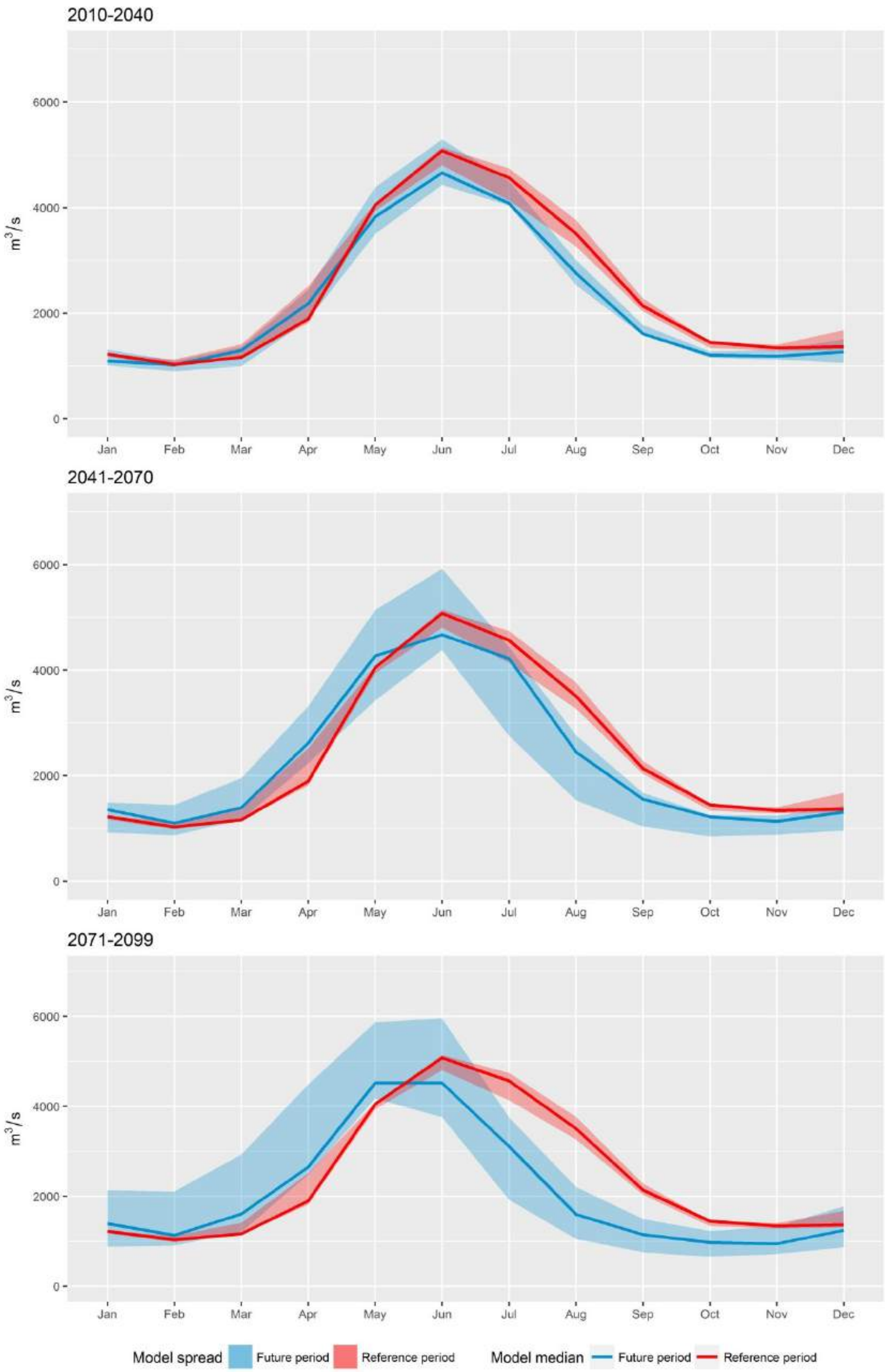

Fig A23 Mean monthly discharge projections, as indicated by multi-model mean and multi-model spread for the Kelif gauging station under the RCP8.5 scenario for reference and three future periods

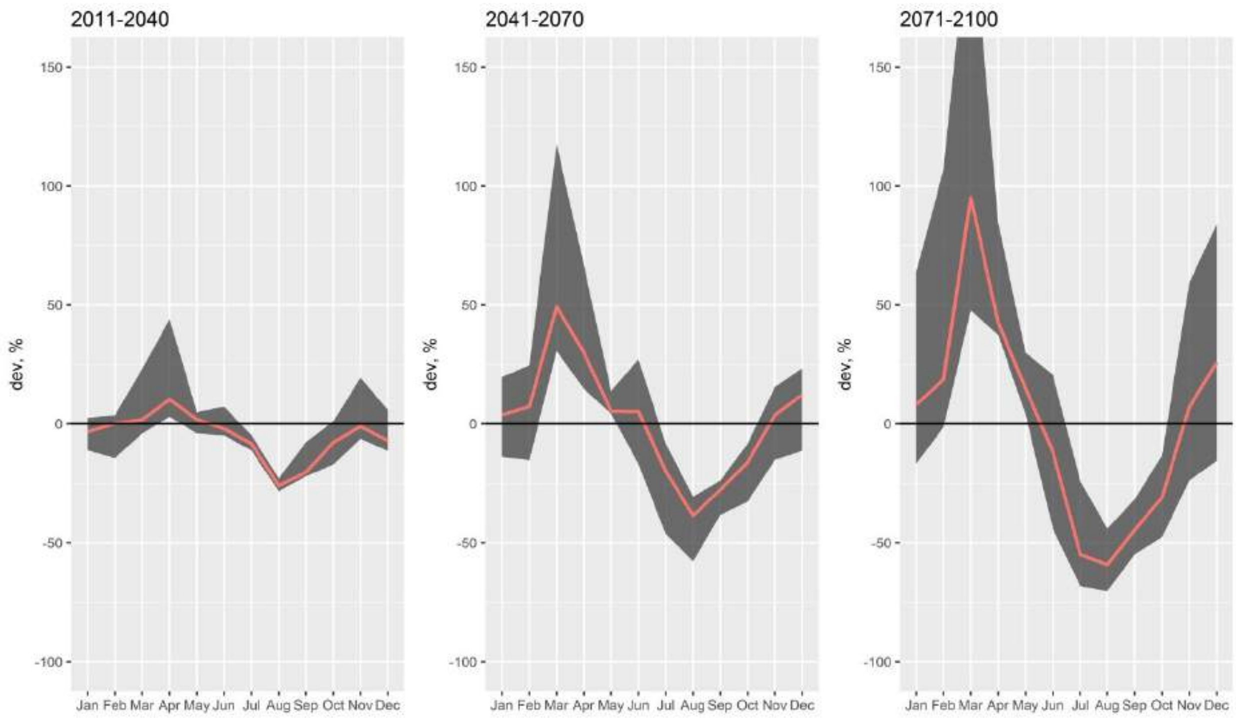

Fig A24 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Tartki gauging station under the RCP8.5 scenario

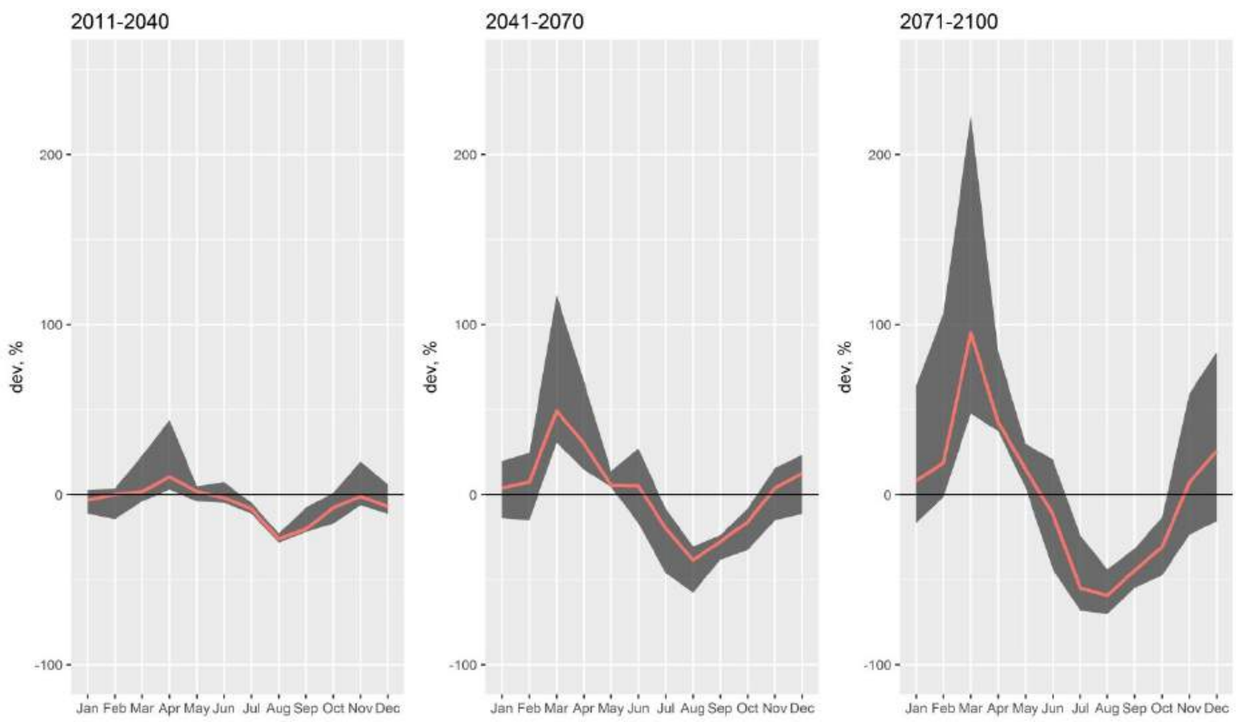

Fig A25 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Kizyl Kala gauging station under the RCP8.5 scenario

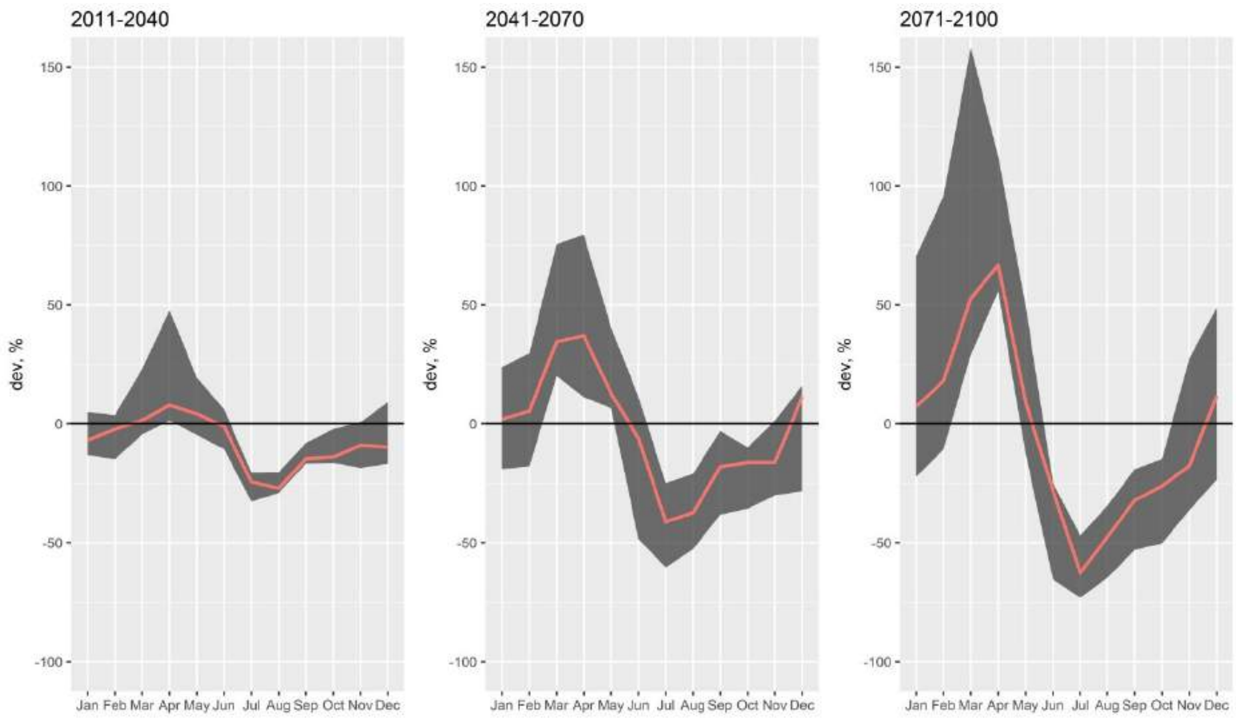

Fig A26 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Nizhniy Pianj gauging station under the RCP8.5 scenario

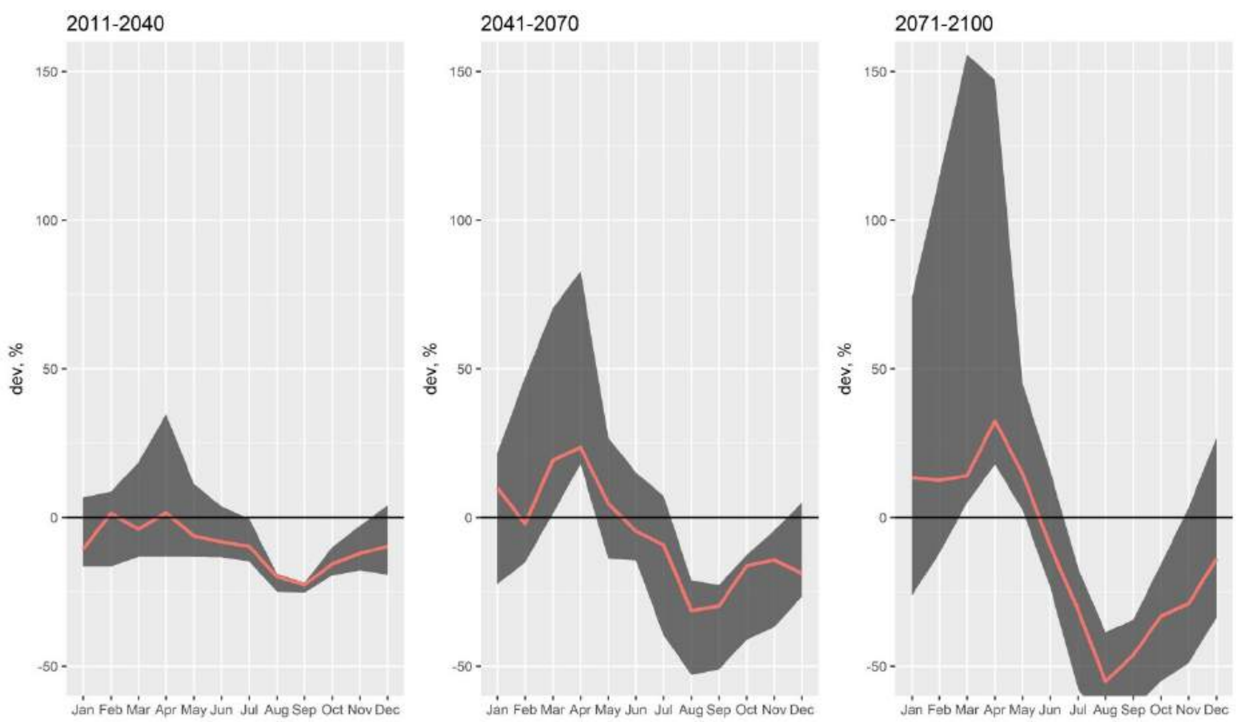

Fig A27 Mean monthly deviation in discharge for three future periods relative to the reference period, as indicated by multi-model mean and multi-model spread for the Kelif gauging station under the RCP8.5 scenario